

Magnetoplasmadynamic Thruster Workshop

*Proceedings of a workshop held at
NASA Headquarters
Washington, D.C.
May 16, 1991*

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I. SUMMARY.

Background. On May 16, 1991, the NASA Headquarters Propulsion, Power and Energy Division (Code RP), and the NASA Lewis Research Center Low Thrust Propulsion Branch hosted a workshop attended by key experts in magnetoplasmodynamic (MPD) thrusters and associated sciences from NASA, the Department of Defense (DoD), the Department of Energy (DOE), and academia. The scope of this workshop was limited to high power MPD thrusters suitable for major NASA space exploration missions, and its purpose was to initiate the process of increasing the expectations and prospects for MPD research, primarily by increasing the level of cooperation, interaction and communication between various parties within the MPD community. Discussions focused primarily on three areas:

- **Planning for the future.** The future success of the MPD program demands that we show significant progress during the next five years in improving the performance of MPD thrusters in terms of key parameters such as efficiency, specific impulse and lifetime. A comprehensive and integrated plan is necessary to ensure that the MPD community maximizes the available opportunities to make those critical, high priority measurements that will do the most to advance our modelling, design and analysis capabilities and expertise. This plan should clearly spell out when and how the program will achieve needed quantitative improvements in the performance of MPD devices.

Long-range plans for the MPD program must also consider the eventual need to evolve into a complete effort that considers the issues associated with all elements of a space transportation propulsion system, including the prime power power source, fuel storage, structures, facility requirements for testing thrusters in regimes of interest, etc. For example:

- Power system mass has a tremendous impact on the performance of low thrust propulsion concepts such as MPD thrusters. As discussed in section IV.C., power system specific mass must be as low as 7 kg/kWe for manned interplanetary missions or MPD thrusters become untenable for all realistic levels of thruster performance. This is a very challenging goal for power system developers.
- **Developing community interaction.** The prospects for developing and deploying operational high power MPD thrusters are also a function of the extent to which we can foster a close-knit and well-coordinated MPD community that works together to accomplish common goals. This workshop, and others that will follow to carry on the process started here, will be invaluable in accomplishing this goal. Specific benefits that are already evident from the current meeting include the following:
 - Increased interaction between mainline MPD thruster researchers and DOE fusion researchers. The fusion research program has previously addressed some of the physics issues now being faced in the development of high power MPD thrusters.
 - Greater input from theoreticians regarding what experimental measurements should have the highest priority in order to advance our overall understanding of MPD processes.

It is also essential that DOE, NASA and academia approach nuclear electric propulsion as a joint effort to build an integrated device. Separate projects by DOE to build a reactor and by NASA to build a thruster will not produce an optimum nuclear electric space propulsion system.

Technical and Programmatic Priorities. Despite the uncertainty of long-range predictions, system analysis makes it very clear that the MPD program's near-term emphasis must be on improving the efficiency of high power thrusters. Unless this goal is accomplished, other accomplishments will mean very little. Near-term plans for data gathering, modelling, etc. should be formulated in terms of how to best meet this objective.

II. ACTION ITEMS.

The following action items were generated during the course of this meeting. Full cooperation in completing these action items is essential to demonstrate that NASA, DOE and academia are indeed starting to work as a team in developing MPD thruster technology.

- A. Follow-on workshops** are needed to continue the progress made at this event in terms of long-range, integrated planning for coordinated activities within the MPD thruster community.
- B. There is a need for a comprehensive survey of relevant MPD thruster models** that compares their capabilities and compatibility with each other and with available data bases.
- C. Representatives of Princeton University and LeRC** will determine the extent to which NASA may be able to provide the additional computational support, particularly with regard to supercomputers, that is needed by ongoing research at Princeton's Electric Propulsion and Plasma Dynamics Laboratory.
- D. Meeting participants should provide the following inputs to Roger Myers** no later than September 15, 1991:
 - Listing of specific areas where theory and experimental data fail to adequately address performance losses associated with MPD thruster electrodes, plasma and plume divergence. Please discuss, insofar as possible, the scaling of performance losses. Which parameters scale and which do not?
 - Listing of specific steps that we should take to address these shortcomings, and a description of the extent to which the suggested plan of action is sensitive to power level.¹
 - Listing of facility instrumentation and diagnostics needed to generate experimental data of interest.

¹For example, one suggestion received during the workshop in response to this query was that in addition to solving dispersion relations associated with plasma dynamics, we must also solve the ordinary differential equations that result from investigations of associated physics (Gerwin).

- Listing of known facilities, especially those with high pumping capacities, that are capable of testing MPD thrusters, along with a statement regarding their ability to conduct tests using either lithium or potassium as the propellant (because of either technical limitations, facility policy, state environmental regulations or other factors).
- Data for facility effects on performance and electrode phenomena. Please provide data to substantiate choice of pressure requirements.
- Inputs on the following matrix of thruster components and their impact on thruster performance and life. For example, looking just at the top row, inputs should address:
 - What parameters control anode performance in terms specific impulse, efficiency and lifetime/reliability?
 - What are the theoretical, experimental and operational issues associated with developing and demonstrating an anode for a MPD thruster capable of satisfying performance requirements in the areas of specific impulse, efficiency and lifetime / reliability?

See page eight for additional comments regarding this matrix.

	SPECIFIC IMPULSE	EFFICIENCY	LIFETIME/RELIABILITY
ANODE			
CATHODE			
INSULATORS			

NASA will use these inputs to improve the linkage between theoretical and experimental investigations planned for the future.

Additional inputs

- Facility impact

E. Bickford Hooper, Lawrence Livermore National Laboratory, will provide to Roger Myers, LeRC, information concerning pumping schemes for long-term high-power testing based on work done in support of fusion research devices.

- Comments on validity of quasi-steady testing. Where is it valid and how can we verify this experimentally.
- It is imperative we develop a plan to test the same thruster at several facilities. It may be possible to use this as a test of quasi-steady results.
- Initiate testing of high power thrusters with appropriate propellants (e.g. H₂).

- Initiate systematic code validation against data for: Princeton Benchmark and Flared Anode thrusters, NASA LeRC Applied Field thrusters, Stuttgart Segmented Anode thrusters.

III. ISSUES.

The last session of the workshop consisted of an open discussion to address five key questions that were distributed to the workshop participants prior to the meeting.

Key Question #1. What are the performance expectations (efficiency and specific impulse) as functions of power and propellant? How do we address this issue in a convincing fashion?

Key Question #2. Which issues can be addressed using quasi-steady state thrusters and how do we unambiguously correlate the results with steady-state thruster operation?

Key Question #3. What are the physical parameters which will control the viability of high power thruster designs? Are there limits on anode power density, insulator temperature or cathode current density? What are the recommended ways of addressing these issues?

Key Question #4. What are the minimum facility requirements for performance / life measurements?

Key Question #5. Are there inexpensive pumping schemes which enable long-term high power testing at low cost?

Each of these questions was the subject of detailed discussions and written comments submitted by the workshop participants. The results of these inputs are summarized below. Where appearing, parenthetical references refer to the source of the particular comment or point-of-view. Note, however, that this document does not serve as a verbatim transcript, and the comments appearing below are a paraphrased summary of the actual discussions.

KEY QUESTION #1 - PERFORMANCE EXPECTATIONS.

What are the performance expectations (efficiency and specific impulse) as functions of power and propellant? How do we address this issue in a convincing fashion?

The only acceptable basis for generating expectations about future performance are validated codes (Turchi) and experimental progress (Byers). In developing expectations, we must also consider the system impacts of proposed MPD thruster systems to ensure that the improved thrusters will be practical for operational platforms.

Four factors impact the MPD community's ability to address the issue of future performance expectations (Myers):

- There is an inadequate data base of test results for propellants and power levels of interest.

There is considerable experimental data for a very limited set of geometries with argon propellant. We must establish a performance data base with hydrogen. The MPD community must ensure that it does not succumb to over-reliance on experimental information contained in available data bases. One symptom of such over-reliance would be the production of theories that merely summarize empirical data without a fundamental understanding of the processes involved.² Also, before expanding into additional data bases, additional investigations and modelling are needed to take full advantage of the existing MPD thruster data that already exist. We have not yet completed essential tasks such as characterizing the basic flow field. Now that we finally have the computational tools to address these issues, we must first proceed in that direction. Otherwise, we cannot know whether the data bases which we wish to use as a foundation for future progress contain spurious effects associated with anomalous phenomena that are not indicative of universal operating principles (Turchi). Although our first priority should be to do this analysis for power regimes of mission interest (Schoenberg), it is imperative that we proceed with whatever data are available regardless of the power level to which it pertains (Turchi).

- There is a deep reservoir of models, but there is no clear linkage between most of them.

Models are invaluable aids that will allow us to examine a wide variety of conditions that we cannot physically test because of resource limitations. Existing models can provide us with the essential information we need,³ but only if we can establish a close working relationship between the modelling, experimental, and device improvement specialists (Turchi). The MPD thruster community must conduct a comprehensive survey of relevant models that compares their capabilities and compatibility with each other and with available data bases (Schmidt). For example, CFD codes must be coupled with thermodynamic models of materials to increase our understanding of thruster dynamics (Messerschmid). One approach to verifying models and tying them together would be to use a standard set of benchmark experiments at different facilities (Martinez-Sanchez). Please note action item.

In addition, we must exercise available models so that we can evaluate the accuracy of the results (Martinez-Sanchez). Even as this validation process identifies problems and shortcomings within the codes, it will undoubtedly improve our understanding of the MPD thruster processes (Schmidt). Nonetheless, we must not overestimate our ability to fully understand and model all of the processes that occur within MPD thrusters. Fusion

²Several workshop presenters were careful to emphasize that theories do not yet exist to explain many of the experimental correlations and phenomena that they have observed.

³Of course, extending the abilities of existing codes would provide clear benefits, particularly in areas such as surface chemistry and other surface effects (Myers). Rather than imply that additional code development is unnecessary, the point of this statement is to emphasize the need to move forward aggressively by using the models that already exist rather than to assume that significant progress in the overall effort to develop MPD thrusters must await the arrival of new modelling capabilities.

research programs have been working for decades to understand physical processes and transport phenomena within high-energy plasmas, yet some mysteries linked to subtle and elusive phenomena remain unsolved. For example, it is impossible to fully explain fundamental differences that appear to exist in the performance of some similar plasma devices. Similarly, processes within different thruster designs may be ruled by different effects, and, if so, this will greatly complicate the effort to link and compare models that have been nurtured and validated using different sets of experimental hardware. Nonetheless, the MPD research effort does have some advantages relative to the fusion development program, particularly with regard to hardware size and the ability to conduct experimental investigations at power (Schoenberg).

We also need to determine how far we can extend experimentally derived curves to higher power levels before the onset of instabilities invalidate the projections (Martinez-Sanchez). Rather than accept onset as an unalterable obstacle, however, we should consider how we can alter design parameters to delay onset and avoid having to pass through these stopping points (Turchi). Even though models may not yet have the capability to fully support all of the work that remains to be done (Martinez-Sanchez), the need for progress demands that we use what we have (Turchi).

We must accept the reality that we do not now and are not likely to soon possess end-to-end codes that will be able to predict complete device performance starting with first principles. We should instead accept the need to, at some points, rely upon intuition and empirical methods so that we can concentrate analytical resources on the biggest loss leaders, such as plasma inhomogeneity, free stream instabilities and anode losses, that are the most challenging of our near-term problems (Jahn). "If we had waited until we understood combustion before we built gasoline engines, we would all still be riding horses."

Three approaches exist as we plan for the future, each with a different emphasis (Martinez-Sanchez):

- Localized processes
- Macroscopic effects
- System-level device optimization

A system-level approach focused on a specific mission has the advantage of supporting a concentrated effort to develop operational devices. This approach would most directly challenge the lead currently enjoyed by the nuclear thermal propulsion (NTP) community (Hastings), although it is not realistic to anticipate succeeding in such an attempt during the next five years. Furthermore, it is impossible to select a single mission of interest; exploration plans and mission requirements are certain to change many times between the point that a firm proposal for space exploration is accepted and the time that it is finally implemented (Watkins). Focusing on localized processes rather than global design seems to be the best approach for achieving maximum growth of MPD thruster technologies in areas of critical interest. (Jahn, Watkins).

- There are three primary loss mechanisms that impact MPD thruster efficiency: electrode losses, plasma losses and plume divergence.

This community has a wide variety of interests and relatively few resources. As a result, we must prioritize and concentrate on those efforts that will be most beneficial to identified missions (Schoenberg). Mission analysis clearly shows that the key to developing operationally useful devices is to improve MPD thruster efficiency (Byers).

Specific activities to address electrode loss issues should include an examination of the Stuttgart results as well as investigations of innovative electrode shapes (Polk).⁴ The cathode does not seem to represent as significant a performance loss.

The effort to reduce plasma losses would be aided by direct measurements of transport parameters such as resistivity and ion temperatures. The latter measurement could be made using Doppler broadening techniques. It may also be advisable to more fully consider the atomic physics aspects of MPD issues (Hooper).

- There is uncertainty about the ability of existing and planned facilities to provide convincing measurements, especially with limited resources to conduct extensive testing.

Measurements inside the thrust chamber, such as those needed to monitor properties at the edge of the sheath, are especially important to our understanding of MPD thruster processes. Unfortunately, they are also extraordinarily difficult, and not inexpensive, to obtain.

KEY QUESTION #2 - QUASI-STEADY STATE VS. STEADY STATE THRUSTERS.

Which issues can be addressed using quasi-steady state thrusters and how do we unambiguously correlate the results with steady-state thruster operation?

Quasi-steady state testing forms the backbone of many existing experimental programs, and it seems clear that some phenomena, such as flow instabilities and the influence of the applied magnetic field, can be correlated between quasi-steady state (QSS) and steady-state MPD thrusters. On the other hand, it seems equally obvious that other areas of importance, such as life and its impact on performance, cannot be accurately determined based upon tests using QSS devices and there is substantial doubt as to the validity of terminal voltage measurements (Myers)⁵. We must obtain an unambiguous data base of direct performance measurements (thrust, voltage, flow rate) from which to address these questions. Longer pulse lengths may also be needed to determine mass flow

⁴The Soviets, in particular, seem to favor the use of extremely complex, magnetically insulated electrodes in QSS plasma guns, although details are hard to come by because much of it is classified. Nonetheless, it may be worthwhile to try and expand our knowledge of Soviet technology in this area.

⁵QSS testing of cathodes uses external preheating to simulate thermal conditions that would be generated during long-term steady-state operations. However, the temperature distributions established in the cathodes by external heating do not necessarily reflect the actual distributions that are established during SS operations.

phenomena during steady state.⁶ At our current level of understanding, however, when we need to account for factors of two between some predicted and experimental results, relatively inexpensive and simple experiments will be sufficient to reduce existing uncertainties (Jahn). Ultimately, however, it may be impossible to satisfy potential users that the physics and performance of steady-state devices is sufficiently well-defined with only quasi-steady test results in hand (Schmidt). Simply stated, the answer to this question depends somewhat on the level of precision that the correlation must demonstrate and the degree of skepticism of the individuals who will decide whether the correlation passes muster. In the long term, a high degree of precision will be needed to ensure that MPD thrusters are suitable for manned missions, and, as a result, there clearly exists a need for steady-state test facilities in long-term plans for the development of MPD propulsion systems.

KEY QUESTION #3 - PHYSICAL PARAMETERS FOR HIGH POWER THRUSTERS.

What are the physical parameters which will control the viability of high power thruster designs? Are there limits on anode power density, insulator temperature or cathode current density? What are the recommended ways of addressing these issues?

As described in paragraph II.D., workshop participants are being requested to help complete the following table in terms of key parameters and theoretical, experimental and operational issues associated with critical thruster components and performance areas.

	SPECIFIC IMPULSE	EFFICIENCY	LIFETIME/RELIABILITY
ANODE	1	2	3
CATHODE	4	5	6
INSULATORS	7	8	9

This table emphasizes the cross-talk between performance and life issues. Changing electrode shape and size to accommodate power or current density limitations WILL impact the performance of the thruster. The community must focus its attention on devices which have reasonable expectation for surviving long term operation.

Information on the following areas was obtained in the course of the workshop:

- Long-life cathodes / anodes (blocks 3 and 6 in the above table). Electrode degradation is seemingly unavoidable, but this problem can be used to advantage in the case of consumable electrodes where the propellant is fed into the thruster using dispenser electrodes (Schmidt).⁷ This approach

⁶With pulses that last only for milliseconds, absorption of gas by chamber walls and other surface effects can significantly impact plasma densities and cause results to deviate from those characteristic of steady-state operations.

⁷See Section IV.K. for additional comments on dispenser electrodes.

transforms the problem from one of preventing electrode erosion to the more tractable problem of predicting and controlling electrode erosion.

- Long-life electrical insulators (block 9 in the above table). Previous experience with other high energy devices indicates that insulators must be shielded from exposure to the plasma (Myers). The need to provide this shielding can obviously have a major impact on device design, and it must be preplanned rather than left as an add-on.

KEY QUESTION #4 - FACILITY REQUIREMENTS.

What are the minimum facility requirements for performance / life measurements?

Facility limitations are a key factor that will effect our ability to conduct high power ground tests in support of future flight experiments. The capacity of vacuum tanks to simulate high altitude flight conditions for extended test runs is just one example of potential problems in this area, and finding a long term solution to this and similar problems certainly merits serious discussion. Nonetheless, we should not let long term uncertainties delay us from taking decisive action in the short term. As with other challenges facing the MPD thruster program, existing tools may not be ideal, but they are sufficient to advance our understanding beyond its current levels, and we should proceed in the short term as best we can with what we have (Myers). "Perfect" is the enemy of "good enough."

In addressing facility requirements, it is also worth noting that there are some differences in experience that warrant investigation, particularly with regard to LeRC, Princeton University and Stuttgart (Myers). Facility requirements MUST BE addressed in the context of the devices tested and their performance levels.

KEY QUESTION #5 - INEXPENSIVE PUMPING SCHEMES.

Are there inexpensive pumping schemes which enable long-term high power testing at low cost?

As already emphasized, the MPD program must make tangible progress in the short term, and, for this reason, low-cost pumping must be viewed as one of the program's top priorities because without it the entire program is limited in its ability to conduct needed high-power demonstrations and experiments (Byers).

LeRC is aware and taking advantage of the pumping study completed by Argonne National Laboratory four-to-five years ago (Myers). Bickford Hooper, Lawrence Livermore National Laboratory, can provide additional information concerning related work that has been done in support of fusion research devices. Specifically, he is familiar with the use of multiple baffled chambers to inhibit gas flow and produce a gas-free neutral beam (Hooper).

Another pumping arrangement that could be used with collimated plumes would be to direct thruster exhaust into a turbo pump (Turchi). Alternatively, in the case of a cryogenic propellant, the plume could be directed downward into and absorbed by a cryogenic pool (Jahn). Diffusers and getters were also suggested as

possible approaches, although the later does not seem feasible for high power applications except to remove impurities.

The Air Force Phillips Laboratory is addressing this problem by using alkali metal propellants. The high melting point of these materials makes it possible to use an inexpensive warm oil system to both maintain vacuum as well as capture and recycle the propellant.

ADDITIONAL ISSUES, CONCERNS AND RECOMMENDATIONS.

During the course of the workshop, participants identified the following additional issues, concerns and recommendations.

1. End points and limitations in published performance curves are sometimes a reflection of external factors such as the investigator's resources scarcity rather than a true representation of absolute limits. A test program may proceed to a certain level of performance and then, because initial goals are accomplished, other tasks become more urgent, or some other distraction, the effort is halted, curves are generated, and the results tabulated. Even when technical difficulties arise that imply physical constraints may exist on achieving higher power or improved performance, alternatives may exist which, if vigorously pursued, would show that progress has not yet encountered hard technological limits.

2. Although current testing indicates that applied external fields are important to the efficient operation of existing MPD thrusters, we may need to develop the ability to operate solely with self-generated magnetic fields for high power applications because:

- The magnitude of the external fields needed to control the operation of multi-megawatt steady-state thrusters may prove to be unmanageable, and/or
- Extremely powerful external magnetic fields may induce their own micro-instabilities that are as problematic as the effects the externally applied fields are intended to control.

We clearly need an experimental data base to answer these questions and establish the potential impact of applied fields at MW power levels.

3. It is essential that experiments measure the ability of MPD thrusters to produce directed thrust, not just plasma excitation. Magnetic nozzles may be a key item in maximizing thrust at all power levels.

4. Increased emphasis should be placed on:

- Impulse balances
- Improved facility diagnostics
- Testing of real propellants such as hydrogen at performance levels of interest

5. Although some facilities such as Phillips Laboratory can still operate with "hazardous" materials without undue regulation from state authorities, this independence seems to be disappearing as states become more willing to involve themselves with perceived environmental hazards on federal reservations. Even

in Europe, some materials such as beryllium are receiving limited consideration for many research and experimental applications because of the extra trouble and expense associated with meeting increasingly stringent environmental protection regulations.

6. The differences that exist between low and high power MPD thruster processes and systems may interfere with the ability to evolve from one to the other, and it may be necessary to develop two different types of devices for different power regimes. In fact, selecting thruster concepts based upon their ability to satisfy near-term performance objectives may inadvertently divert attention away from alternative concepts that work well only at high power levels. We must address this issue in a specific technical fashion to establish which parameters will permit scaling and which will not. Inputs were requested (Section II).

7. The benefit of electrode redeposition in reducing net electrode erosion rates, as noted in footnote 12 and Section IV.L. of this report, may not occur in operational systems depending on their geometry and pressure levels. Related data from the Institute of Stuttgart should be treated with care for this reason.

8. Cathode procurement is one area where collaboration could provide mutual benefits. Many existing MPD thruster test facilities undoubtedly procure their cathodes from the same supplier. Ordering cathodes in small quantities of various designs maximizes cost, delivery time and the difficulty of correlating experimental results from different facilities. This situation would be reversed if several facilities acted together to analyze future requirements and then ordered a single lot of cathodes consisting of variations on the same basic design.

IV. PRESENTATIONS AND DISCUSSIONS.

The following is a summary of the presentations and key discussions that took place during the workshop and which are not already summarized above. Additional information is contained within the briefing packages, copies of which are included in the appendices.

A. NASA HEADQUARTERS, POWER, PROPULSION AND ENERGY DIVISION.

This section summarizes the comments made during the course of the workshop by the three Headquarters representatives in attendance: Gary Bennett, Earl VanLandingham and Marcus Watkins.

Many thruster concepts exist under the umbrella of the nuclear electric community, but MPD and ion thrusters are clearly ahead of all the others. Nonetheless, clear, measurable progress within the next five years is essential to the health of the overall MPD thruster program, and the MPD community must determine a way to generate this progress without the luxury of increased research budgets. If NASA were to focus on an early (2014) trip to Mars, nuclear thermal propulsion technology would clearly offer reduced risk relative to nuclear electric propulsion, particularly because of the systems work which is not yet taking place within the nuclear electric propulsion development effort.⁸

⁸Recent efforts, such as the nuclear electric workshop that brought together representatives from the reactor and thruster communities, are starting to address this shortcoming. Boeing is also doing systems work for nuclear electric propulsion.

Fortunately, there is no immediate need for proponents of nuclear electric propulsion to compete head-to-head with alternative propulsion concepts. Space exploration will involve a number of goals spread over the next two or three decades, and even the nuclear thermal propulsion program is having trouble meeting some of its existing program milestones. Furthermore, advanced propulsion technologies represent essential long-lead-time technology that needs support far in advance of a final decision to execute a particular mission or set of missions. However, it is essential that the MPD Thruster program clearly demonstrate significant progress in key areas such as efficiency and scalability in order to move the program into a more favorable position. As a community, we must identify how to evolve MPD thrusters, test them, and earn the confidence of mission planners by making them familiar with MPD research as it relates to their system requirements.

DOE's participation in this workshop was very welcome. In addition to the benefits provided by their past experience in plasma research, it may be possible for National Laboratories to use some of the \$30 M that DOE has requested for the Space Exploration Initiative to support MPD thruster R&D. NASA / DOE interaction is also occurring in other activities at both the headquarters and field center/laboratory level.

Developers of future systems must be flexible in order to satisfy mission requirements which may evolve in unexpected directions. With regard to MPD thrusters, one of the areas in which this phenomena manifests itself is the selection of propellants. At present, hydrogen is recognized as an acceptable candidate from a systems engineering and performance point of view, although other potential propellants should also be evaluated to provide viable alternatives that may offer superior performance.⁹

B. MPD THRUSTER WORKSHOP, DAVID BYERS, LERC.

Nuclear electric propulsion, together with nuclear thermal propulsion, make up the two halves of the nuclear propulsion program. The pursuit of high power MPD thrusters can follow either an evolutionary approach or an Apollo-like tiger-team approach. The evolutionary approach seems to be most consistent with anticipated space exploration missions, which are likely to evolve from relatively simple lunar and Mars robotic missions to the extremely challenging piloted Mars missions. Furthermore, an evolutionary approach is consistent with the historical philosophy of the electric propulsion community. An Apollo-like approach is also difficult to orchestrate when the final objectives are still undefined and likely to remain so for the foreseeable future – even if firm goals are established in the near term, recent experience with major space projects makes it seem unlikely that announced goals would remain constant during the long period of time necessary to mount a major space exploration effort. Nonetheless, it should be possible, though certainly non-trivial, to construct a technology program that will be able to accommodate existing uncertainties in

⁹The Air Force is preparing to test composite tanks at pressures ranging from 20,000 to greater than 50,000 pounds per square inch. At these pressures, hydrogen gas storage systems become competitive with cryogenic storage systems – although high pressure tanks are not particularly lightweight, gas storage eliminates the need for a variety of bulky and complex piping needed for cryogens.

propulsion requirements. Although there is certainly a long way to go before MPD thrusters can satisfy propulsion requirements for piloted interplanetary missions, demonstrated performance is not too far from satisfying early mission requirements. Nonetheless, the MPD community faces stiff competition from other propulsion communities with their own sincere, dedicated advocates.¹⁰

An initial period of five years has been selected to define the technologies appropriate for further development, and it is important to the survival of MPD thrusters as a viable propulsion system option within NASA to complete significant performance demonstrations within that period of time. These demonstrations should specifically feature improvements in efficiency, specific impulse, power and lifetime as well as examine the potential impact of exhaust plumes on the host platform. Clearly, we must carefully craft the limited number of tests that available resources can support in order to maximize their payoff.

Although Soviet experience with potassium and sodium propellants used with auxiliary MPD thrusters has shown that propellants can return to the spacecraft and cause contamination problems, this effect could be significantly reduced with a main engine MPD thruster, even with non-benign fuels such as reactive metals. Unlike auxiliary propulsion systems, main engines are ideally located on the spacecraft to minimize plume contamination, and other operations are typically secured during main engine operation.¹¹

C. NUCLEAR ELECTRIC PROPULSION MISSION SENSITIVITIES, JIM GILLAND, SVERDRUP TECHNOLOGY.

The mission analyses reported in this presentation focused on four system parameters:

¹⁰Although many alternative concepts appear to be closer to fruition in terms of operational systems, they also have peculiar problems of their own, the ultimate impact of which is impossible to predict. Nuclear thermal propulsion concepts face severe environmental challenges in conducting high power testing on the ground or in the Earth's atmosphere. Aerobrake systems will have a difficult time demonstrating man-rateable levels of reliability and safety, especially for entry into the Martian atmosphere.

¹¹Of course, planetary transfer vehicles using MPD thrusters for primary propulsion would need to operate their main engines during a much greater fraction of the total mission time than would chemical main engines. As a result, the operation of MPD thrusters will need to be compatible with most operations planned for the in-transit and planetary capture portions of the mission profile.

PARAMETER	SIGNIFICANCE	ANALYSIS RESULTS
SPECIFIC MASS OF THE ELECTRICAL POWER SOURCE (KG/KWE)	TRIP TIME LIMITS	SPECIFIC MASS IS THE KEY DRIVER TO REDUCE TRIP TIMES, BUT IT DEPENDS PRIMARILY ON THE POWER SOURCE HIGH VALUES OF SPECIFIC MASS INCREASE SYSTEM SENSITIVITY TO ENGINE EFFICIENCY
ENGINE EFFICIENCY (PER CENT OF ENGINE INPUT ENERGY CONVERTED TO USEFUL THRUST)	TRIP TIME PROPELLANT MASS	EFFICIENCIES AS LOW AS 25% MAY BE COMPETITIVE FOR LUNAR CARGO MISSIONS, BUT ULTIMATE GOALS MUST BE >50% TO PROVIDE ACCEPTABLY LOW TRIP TIMES FOR PILOTED MARS MISSIONS
SPECIFIC IMPULSE OF THE PROPULSION SYSTEM (SECONDS)	PROPELLANT MASS REQUIREMENTS	SPECIFIC IMPULSE HAS A SECONDARY IMPACT ON MISSION PERFORMANCE, AND THE DEPENDENCE OF THRUSTER EFFICIENCY ON SPECIFIC IMPULSE WILL AFFECT THE CHOICE OF SPECIFIC IMPULSE
SYSTEM POWER LEVEL (KWE)	TRIP TIME PAYLOAD MASS CAPACITY	POWER LEVELS OF INTEREST RANGE FROM 1-10 MWE FOR LUNAR CARGO MISSIONS UP TO TENS OF MWE FOR PILOTED MARS MISSIONS

Appendix D. details the specific mission parameters used for the three cases analyzed: orbital transfer, planetary cargo, and piloted interplanetary. The long lifetime and high energy requirements of interplanetary probe missions seem to rule out MPD thrusters for that application, and this application was not included in the analysis of MPD missions.

LeRC has developed a spacecraft evolution scenario in the last few months that describes how power systems could evolve along with mission requirements to produce a series of related spacecraft. The same principle could apply to the propulsion system. Of course, the emphasis on spacecraft evolution heightens the need to establish the most stressing Mars exploration missions as the ultimate long-term MPD program goal. It is unlikely that a particular propulsion system will be selected for the initial missions unless exploration program managers are convinced that it has the potential to grow in capability and carry through to the end. It is also unlikely that developing more than one primary propulsion system will be affordable.

Analysis results in Appendix D for piloted missions do not include planetary spiral time in the mission duration, based upon the assumption that the crew would transfer to/from the vehicle at high altitude, leaving the vehicle to spiral in an unmanned condition. The small amount of additional ΔV that this demands from the Mars exploration vehicle used for planetary descent and ascent results in minimal additional requirements for initial mass in low Earth orbit (IMLEO).

The IMLEO vs. trip time plots depicted in Appendix D include a chemical/aerobrake reference line at the estimated mass of a chemical/aerobrake system. This line does not depict the trip time of chemical/aerobrake systems which, especially for lunar missions, would be much less than the trip times for nuclear-electric propulsion systems.

Most of the analysis results contained in Appendix D assume a power system specific mass of 10 kg/kWe. As the value of this parameter increases, total vehicle mass increases, which tends to increase trip time. Increasing thruster capacity can offset this increase in trip time, but larger thrusters require more power, which implies the need for a more massive power plant, which offsets the benefit of the more powerful thruster. For lunar cargo missions, a power system specific mass as high as 20 kg/kWe is mass-competitive with chemical/aerobrake systems if MPD thrusters can demonstrate 40% efficiency and mission planners are willing to accept trip times of 100 to 125 days each way. Reducing specific mass by a factor of two (to 10 kg/kWe) also cuts trip time in half for the Lunar cargo scenario. However, piloted Mars missions are so strenuous that power system specific mass must be as low as 7 kg/kWe or MPD thrusters become untenable regardless of thruster efficiency. Developing a 7 kg/kWe power system will be very challenging, although this task is outside the scope of the existing MPD thruster development effort.

The plots in Appendix D do not depict the mass of all-chemical systems. For Mars missions, an all-chemical system would probably require an IMLEO on the order of 2000 tons compared to 800-900 tons for a chemical/aerobrake system.

The mass advantage depicted for electric propulsion systems increases even more than shown when considering the case of reusable vehicles because of the small amount of propellant consumed per trip compared to chemical engines.

Propulsion system run time closely approximates trip time for nuclear electric systems, especially for near-Earth missions. Even for Mars missions, the propulsion system would need to operate for 60% to 75% of an 800-day mission.

D. THE MPD THRUSTER PROGRAM AT JPL, JOHN BARNETT AND JAY POLK, JPL

Analysis at JPL confirms that nuclear electric propulsion offers mass advantages over nuclear thermal or chemical/aerobrake systems for high power levels (>10 MWe) and low specific mass (<10 kg/kWe). In addition to the thruster, a nuclear electric propulsion SYSTEM also includes a nuclear reactor, power converter, power management and distribution system, power processing system, and thermal management system. Funding of many of these key areas is faring no better than the thruster development effort.

Appendix E summarizes the requirements, status and JPL's recommended approach for the following critical issues associated with the development of MPD thrusters:

- System Level Issues
 - Definition of operational requirements
 - Thruster-spacecraft interactions
- Component Level Issues
 - Operating power level
 - Specific impulse
 - Efficiency
 - Lifetime

- Thermal management
- Facility requirements

Appendix E also describes JPL's existing activities in support of MPD thruster development. A portion of their current effort is devoted to evaluating the potential benefits of alkali metal propellants. Following a preliminary assessment of the systems-level impact of alkali metal propellants, they will determine whether to proceed with the next phase of study which would investigate the three primary issues associated with this class of propellants:

- The effect of alkali propellants on the cathode work function
- Overall improvements in thruster performance
- The potential for contamination of the host platform.

Most of JPL's current testing is limited to low power levels and, like others, they are faced with the challenge of extrapolating low-power results into high power regimes. JPL has collected interesting data concerning diffuser effects on tank pressure at various power levels (5-35 kW) using argon propellant. They are still investigating possible interactions between the plume and the diffuser to develop an explanation for the observed data (see Appendix E).

E. LLNL CONTRIBUTIONS TO MPD THRUSTERS FOR SHI, R. BACKFORD HOOPER AND JIM HAMMER, LLNL.

In the course of their tokamak fusion research, Lawrence Livermore National Laboratory (LLNL) has encountered many of the same kinds of plasma physics issues that the MPD program faces. Although it would not be appropriate for LLNL to propose major new initiatives in MPD research because of the acknowledged funding limitations faced by the MPD program, at some point NASA must demonstrate its willingness to provide some support to LLNL in order to sustain a substantial level of collaboration concerning MPD research.

Enclosure F describes the near- and short-term contributions that LLNL can make to the MPD program in the following areas:

- Modelling
 - MPD characteristics
 - Atomic-plasma interactions
 - Plasma material interactions that effect erosion/sputtering and redeposition of tungsten and carbon¹²
- Measuring MPD and plasma effects
- Remote measurements of density, temperature and magnetic field strength

¹²Plasma/material interactions are very important to MPD thruster electrode life and performance. Experimental studies by LLNL indicate that local redeposition of eroded material can reduce net erosion rates by more than an order of magnitude.

- High power testing of MPD thrusters for lifetime validation using the MPTF-B facility.¹³

Appendix F also describes LLNL's Ring Accelerator Experiment (RACE) and the Two-dimensional Ring Acceleration Code (TRAC) that they have used to model RACE hardware performance.

Jim Hammer briefly discussed the possibility of using the highly-conducting plasma exhaust plumes generated by a device such as a MPD thruster to extract electric power from the solar wind as a result of interactions with interplanetary magnetic fields. The tremendous extent of exhaust plumes offers the potential for producing greater than 10 MW of power using thrusters based either on a spacecraft or at a lunar base. In the case of a spacecraft thruster, the generation of electrical potentials may occur even if not desired, perhaps resulting in electrical discharges through low-impedance paths if not anticipated by spacecraft designers. Individuals interested in more information on this topic should contact Jim Hammer and request a copy of his paper, *Plasma Plumes for Tapping the Electromotive Force of the Solar Wind*.

F. MPD THRUSTER TECHNOLOGY AT LERC, ROGER M. MYERS, DEVELOPMENT TECHNOLOGY.

The experimental MPD thruster research program at LeRC is focused on the development of steady-state thrusters at powers up to 1 MW; the maximum power is based on facility limitations. LeRC has completed testing up to 230 kW, and testing should reach the 500 kW-to-1 MW level as soon as thruster cooling capacity is increased. Appendix G presents an overview of recent experimental results, including electrode geometry and facility pressure effects.

Comparative testing of hydrogen and argon propellants under identical conditions show that for a given mass flow rate, hydrogen offers significant advantages in terms of efficiency and specific impulse. Ongoing efforts are using experimental testing to validate MPD codes. Presently, codes are unable to incorporate the complexities associated with the operation of MPD thrusters using applied magnetic fields, and attempts to operate high power thrusters while reducing the applied field have produced rapid erosion. LeRC is proceeding to develop an applied-field version of its MPD thruster code while continuing to investigate the prospects for self-field operation. LeRC is also investigating the impact of alternative propellants such as helium, nitrogen, and lithium on thruster performance. Lithium, in particular, seems to show promise based on published research concerning its potential for improved specific impulse and efficiency, although the extreme difficulty of measuring lithium mass flow rates raises some concerns about the published results.

G. LOS ALAMOS NEP RESEARCH IN ADVANCED PLASMA THRUSTERS, ERNST SCHOENBERG AND RICHARD GEWIN, LANL.

Los Alamos National Laboratory, (LANL) has initiated an advanced plasma thruster program that capitalizes on its existing capabilities in plasma science

¹³This is just one of many expensive research facilities owned by the U.S. government that are underutilized or dormant because of insufficient operating funds.

and technology. The LANL effort is investigating scaling issues as a means of addressing multi-megawatt (MMW), large-scale, quasi-steady state MPD thruster performance. Appendix H describes how LANL is using a coaxial plasma gun, which has many similarities with MPD thrusters, to explore experimental and modeling issues associated with the MPD program. Based on their current results, LANL reports that radiative losses within the plasma are small (<10%). Measurements of spatial and temporal distributions of magnetic fields, electric fields, plasma density, electron temperature, and ion/neutral energy are underway.

LANL is also investigating differences in operation with and without applied external fields, and they have concluded that applied fields are important in maintaining a quiescent discharge.

LANL hypothesizes that phenomena associated with large-scale devices may be important to optimize the performance of MPD thrusters for MMW mission applications by reducing current density, by producing smaller gradient scale lengths, by transitioning from resistive to more ideal regimes of MPD operation, and by lowering plasma turbulence, which should directly result in higher device efficiencies.

H. MPD WORK AT MIT, MANUEL MARTINEZ-SANCHEZ, MIT.

The limited external support of MPD thruster R&D work at the Massachusetts Institute of Technology limits their work to theoretical investigations.¹⁴ Current efforts are focused on one- and two-dimensional modelling of fluid dynamics and the physics of thrusters using self-generated magnetic fields. They report that the Hall effect is critical to a complete understanding of plasma flows, but it greatly complicates the required computations.

At high current and low mass flow rate conditions, MIT investigators have observed the onset of several phenomena that coincide with limits on efficiency and specific impulse:

- Sharp rise in unsteadiness
- Increased wall erosion, which is closely related to current concentrations
- Large anode drop – this effect is not always present and can be alleviated by injection of anode gas
- Transition from V/I to V/I^3 – this is probably unrelated, although it has been associated with onset

MIT is working to develop complete theories that explain these observations. Additional details are contained in Appendix I.

I. MPD THRUSTER RESEARCH ISSUES, ACTIVITIES AND STRATEGIES, PETER TURCHI, OHIO STATE UNIVERSITY.

Appendix J provides an excellent discussion of MPD thruster research issues (efficiency, specific impulse, lifetime and system performance) and suggested approaches for addressing these issues both individually and as part of a national

¹⁴With the exception of off-site experiments conducted by graduate students at other facilities

strategy to move thruster technology forward. Ohio State advocates an aggressive philosophy that reexamines conventional wisdom, takes advantage of new tools such as advanced computational methods, and searches for innovative approaches. For example, the best approach to eliminate onset may be to develop entirely new components that take the place of components such as electrodes that have known performance limitations.

The plan of attack suggested by Ohio State is not limited to research conducted at megawatt power levels. Increases in efficiency, perhaps by manipulating magnetic fields and by improving electrode performance, must be demonstrated even at 100 kW. Although fundamental differences certainly may exist in the dominant processes that occur in sub-megawatt and multi-megawatt devices, there is a need for efficient thrusters even at these lower power levels and some aspects of device operation, such as critical wavelength along the current flow direction, may be consistent across the entire range of interest. Furthermore, innovations such as magnetic nozzles may be important to maximize thrust efficiency regardless of power level. Concrete advances at any power level are preferable to ambitious plans focused on high power levels that require non-existent funding and facilities to execute.

J. MPD EXPERIMENTAL FACILITIES, ALAN SUTTON, PHILLIPS LABORATORY, EDWARDS AFB.

Phillips Laboratory is building a new electric propulsion test facility that will support development of arc jet, MPD quasi-steady state, and MPD steady-state thrusters. The QSS MPD facility, which is currently operational, has a design pumping capacity of 10^{-4} Torr with 60mg/sec of argon. The steady-state facility will be completed in September 1992.

K. AIR FORCE STEADY STATE MPD THRUSTER DEVELOPMENT, MAJ. WAYNE SCHMIDT, PHILLIPS LABORATORY, EDWARDS AFB.

Unlike the bulk of the MPD thruster community, Major Schmidt has a clearly defined goal: produce a 100kWe MPD thruster with a specific impulse of 1500 sec, an efficiency of 50%, and an operating life of 2000 hours in order to support near-Earth orbital transfer missions.¹⁵ He intends to accomplish this goal by developing a wire-fed thruster using sodium propellant. Major Schmidt is convinced that protection of the electrode, using either a consumable electrode design or a similar alternative such as a porous electrode with gaseous propellant diffusing through it, is critical to the success of near-term operational MPD thrusters. His baseline design will use propellant wires to serve as both cathode and anode, thereby eliminating the lifetime-limiting problem of electrode erosion associated with fixed, non-consumable electrode designs. In fact, it may be advantageous for his thrusters to operate above onset in order to produce the level of electrode erosion needed to generate the plasma. Other advantages of solid dispenser electrodes include:

¹⁵These performance specifications resulted from trade-off analyses involving trip time and payload capacity. The power specification of 100 kWe is approximate, and the proposed design should be compatible with power levels from 50 kWe up to 200-300 kWe. The upper end of this range is compatible with the expected output power of an SP-100 reactor system operating with an upgraded power conversion system.

- The phase changes of the propellant wire from solid to liquid to vapor reduce electrode operating temperature as well as minimize heating of the overall structure
- The use of a solid fuel eliminates problems associated with the storage and management of liquid or high pressure gas propellants
- The melting point of the propellant enables the use of an inexpensive warm oil ground test vacuum pumping system with propellant recycling capability

Major Schmidt, however, readily acknowledges the challenges that he still faces. These include the fabrication of the first MPD steady-state thruster test stand at Phillips Laboratory. Alkali metals also present their own problems in terms of storage, safety, materials compatibility and potential plume contamination during fabrication, storage, test and operation. The development program will address these issues as well as other unknowns associated with the use of dispenser electrodes. The proposed Air Force program will also examine the suitability of using lithium propellants for MPD thrusters suitable for Mars exploration missions.

L. ELECTRIC PROPULSION AND PLASMA DYNAMICS LABORATORY, ROBERT JAEN, PRINCETON UNIVERSITY.

The single most important accomplishment of Princeton University's Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL) has been the training of over 100 graduate scientists in the nearly 30 years of its existence, including six in attendance at this workshop (in addition to the Princeton representatives).

EPPDyL views the world of MPD thrusters as a 3x3x3 set of key elements that is very similar to the 3x3 matrix displayed in paragraph II.D. The nine elements of the EPPDyL construct, which should properly be depicted as cube with a set of three issues assigned to each axis, are as follows:

HIGH POWER LEVELS (>200 kW)	ANODE	SPECIFIC IMPULSE
HYBRID POWER LEVELS (-30 to -200 kW)	CATHODE	EFFICIENCY
LOW POWER LEVELS (-3 to -30 kW)	WORKING FLUID	RELIABILITY

The only significant differences between this matrix and the one in paragraph II.D. is as follows:

- The matrix in paragraph II.D. lacks one dimension because the scope of NASA's mainline MPD thruster program is limited to high power applications.
- The matrix in paragraph II.D. includes "insulators" in place of "working fluid," which appears above.

EPPDyL has experimented with cathode materials such as lithium- and barium-impregnated tungsten to improve cathode performance relative to thoriated

tungsten cathodes. Cathodes with work functions less than two volts and truly minimal evaporative loss rates appear to be achievable. Measured rates of material loss are much less than predicted rates, indicating that redeposition may be reducing the net rate of cathode erosion.

Other experiments at EPPDyL have correlated anode fall voltage and the electron Hall parameter, as indicated in Appendix M, although Princeton investigators have not developed a model that explains the observed relationship. Anode losses are likely to remain a dominant factor in MPD thrusters because of problems associated with the removal of waste heat. Other losses mechanisms such as plasma micro-instabilities will require substantial basic research before the MPD program is likely to meet specified performance goals.

M. MPD THRUSTERS TECHNOLOGY, ERNST MEISSNER SCHMID, INSTITUT FÜR RAUMFAHRTSYSTEME¹⁶ (IRS), UNIVERSITY OF STUTTGART.

Having identified the need for improved numerical understanding of electric propulsion technology, IRS researchers have developed Navier-Stokes models to assist them in their work. Future experiments include testing of a identical MPD thrusters with and without throat constrictions to determine the effect of throat constriction on thruster operation. Additional details on research in progress at IRS is contained in Appendix N.

¹⁶Institute for Space Systems*

Appendix A
NPO Thruster Technology Workshop

The NPO Thruster Technology workshop will be held in Suite 300 East of Capital Gallery, 600 Maryland Avenue, S.W. (202-453-9300). This is across 6th Street from NASA Headquarters. Get off the Metro at L'Enfant Plaza and exit station onto Maryland and 7th.

To maximize the productivity of the meeting, we ask that the presenters bring 30 copies of their presentation. Forms will be provided to all participants to record responses to the five questions posed in the earlier correspondence and any others identified at the meeting. These will be used to guide the group discussion from 3:30 to 5:30. Following the meeting, a volume will be generated incorporating the presentations and a summary of the group discussion.

AGENDA

8:30	Introduction Marcus Watkins, NASA HQ David Byers, NASA Lewis Research Center
9:00	Mission Analysis/Applications
9:30	Jet Propulsion Laboratory
10:00	Lawrence Livermore National Laboratory
10:30	Lewis Research Center
11:00	Los Alamos National Laboratory
11:30	Massachusetts Institute of Technology
12:00-1:00	Lunch
1:00	Ohio State University
1:30	OLAC/Phillips Laboratory
2:00	Princeton University
2:30	University of Stuttgart
3:00	Break
3:30-5:30	Group Discussion 1. Establish key technical issues. 2. Establish program objectives and milestones to address them.
5:30	Summary Roger Myers, Sverdrup Technology, NASA Lewis Research Center

Appendix B

MPD Thruster Workshop Participants

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Appendix C

MPD THRUSTER

WORKSHOP

MAY 16, 1991

WASHINGTON, D.C.

BACKGROUND

- NASA PLANNING/IMPLEMENTING TECHNOLOGY PROGRAMS TO SUPPORT FUTURE, MAJOR MISSIONS
- MISSION SET OBJECTIVES, TIMELINESS, & SCOPES IN PLANNING PHASE
 - EVOLUTIONARY MODE RECEIVING STRONG ATTENTION (PRECURSORS, MOON, MARS, BEYOND (?))
 - APOLLO APPROACH ALSO CONSIDERED

- LACK OF MISSION SET SPECIFICITY WILL REMAIN THRU PLANNING PHASES
- TECHNOLOGY PROGRAMS NEED TO ACCOMMODATE THE MISSION PLANNING PROCESS

BACKGROUND

NASA R&T ELECTRIC PROPULSION UNDER AEGIS OF:

- **BASE R&T (CODE RP/MARCUS WATKINS)**
 - **SUSTAINED PROGRAM**
 - **BROAD/EVOLUNTIONARY TECHNICAL CONTENT**
 - **APPROXIMATELY CONSTANT LEVEL**
- **NUCLEAR PROPULSION PROGRAM (MULTI AGENCY PLANNING UNDERWAY/GARY BENNETT)**
 - **HIGH POWER NUCLEAR PROPULSION (NEPS)
ELECTRIC ONLY**
 - **GROWTH NEPS PROGRAM PLANNED**

BACKGROUND

**A PERIOD OF ~ 5 YEARS SELECTED TO DEFINE
TECHNOLOGIES FOR FURTHER DEVELOPMENTS**

- **LEVEL OF DEMONSTRATION REQUIRED IS HIGHLY JUDGEMENTAL
AND LIKELY MISSION SET SPECIFIC**
- **MINIMUM DEMONSTRATIONS TO JUSTIFY SELECTIONS LIKELY
INCLUDE VALUES (APPROPRIATE FOR TARGET MISSIONS):**
 - **PERFORMANCE LEVELS (η vs Isp)**
 - **POWER**
 - **SUBSYSTEM TECHNOLOGY FOR SPECIFIC MASS
(NOT PACKAGED)**
 - **LIFE CONFIDENCE**
 - **PLUME IMPACT ACCEPTABILITY**

BACKGROUND

MPD THRUSTER SYSTEMS ARE ONE OF SEVERAL PROPULSION CANDIDATES

- CHEMICAL
- CHEMICAL/AEROBRAKE
- NUCLEAR THERMAL ROCKETS
- ELECTRIC PROPULSION
 - ION
 - MPD
 - OTHERS

MPD THRUSTER SYSTEMS WILL BE VIEWED IN CONTEXT OF ALTERNATIVE CONCEPTS

MPD THRUSTERS

STATUS

- DEMONSTRATED PERFORMANCE & OPERATING LEVELS SIGNIFICANTLY BELOW KNOWN MISSION REQUIREMENTS
 - CLOSEST TO POTENTIAL EARLIEST MAJOR MISSIONS (MOON & MARS CARGO)
- TESTING REPRESENTS A MAJOR ISSUE
 - TECHNICALLY
 - PROGRAMMATICALLY

MPD THRUSTERS

THE CHALLENGE

**IDENTIFY SPECIFIC DIRECTIONS/APPROACHES THAT WILL
MAXIMIZE MPD THRUSTER EXPECTATIONS**

- TECHNICAL & PROGRAMMATIC CONSTRAINTS EXIST**
- IMPORTANT TO CONSIDER ALL MISSION OPPORTUNITIES**

AGENDA

8:30 **Introduction**
 Marcus Watkins, NASA HQ
 David Byers, NASA Lewis Research Center

9:00 **Mission Analysis/Applications**

9:30 **Jet Propulsion Laboratory**

10:00 **Lawrence Livermore National Laboratory**

10:30 **Lewis Research Center**

11:00 **Los Alamos National Laboratory**

11:30 **Massachusetts Institute of Technology**

12:00-1:00 **Lunch**

1:00 **Ohio State University**

1:30 **OLAC/Phillips Laboratory**

2:00 **Princeton University**

2:30 **University of Stuttgart**

3:00 **Break**

3:30-5:30 **Group Discussion**
 1. Establish key technical issues.
 2. Establish program objectives and milestones to address them.

5:30 **Summary**
 Roger Myers, Sverdrup Technology, NASA Lewis Research Center

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Appendix D

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P-12

NASA

LEWIS RESEARCH CENTER

NEP MISSION SENSITIVITIES

JIM GILLAND
SVERDRUP TECHNOLOGY, INC.
MAY 16, 1991

ADVANCED SPACE ANALYSIS OFFICE

NASA

LEWIS RESEARCH CENTER

NEP MISSION REQUIREMENTS

- Parameters of Interest

- α - Specific Mass (kg/kWe) - Determines Trip Time Limits
- I_{sp} - Specific Impulse (seconds) - Determines Propellant Mass
- η - Efficiency - Affects Trip Time and Propellant Requirements

- Presentation Approach

- Illustrate the effects of above parameters when considered independently

ADVANCED SPACE ANALYSIS OFFICE



LEWIS RESEARCH CENTER

NEP Mission Evolution

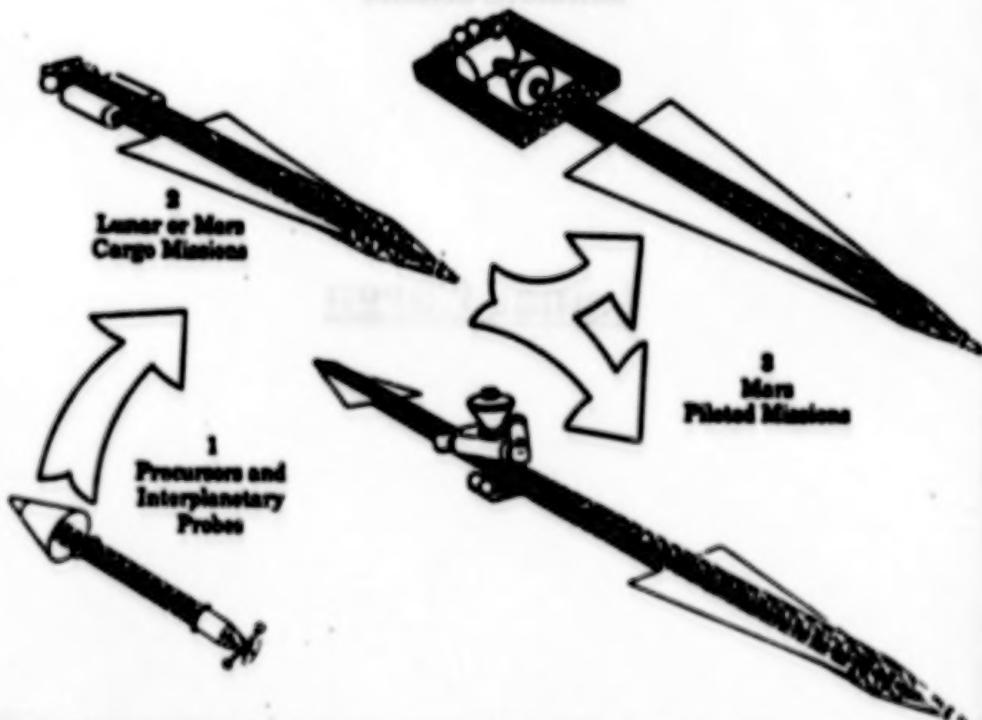
- **Interplanetary Probe**
 - Near term application w/ SP-100, Ion engines
 - Outer Planets - Neptune, Pluto, Jupiter
 - Long lifetime missions
 - Most demanding in terms of energy requirements
- **Orbital Transfer***
 - Low to Moderate Power (.1 - 1 MWe), α (10 - 50 kg/kWe) requirements
 - Includes LEO-GEO, Lunar
 - Planetary gravity well limits EP to cargo trip times
 - Approximate trajectory by ΔV 's of 6 - 8 km/s
- **Planetary Cargo***
 - Moderate Power (1 - 5 MWe), α (10 - 20 kg/kWe) requirements
 - Larger Payloads (100 - 200 MT) Drive Power Level
 - Includes planetary spirals and heliocentric transfer
 - Reduced importance of trip time eases technology requirements
- **Piloted Interplanetary***
 - High Power (10 - 50 MWe), Low α (<10 kg/kWe) requirements
 - Trip time drives α , Power requirements
 - More Trip Times of 1 - 1.5 years are desirable

ADVANCED SPACE ANALYSIS OFFICE



LEWIS RESEARCH CENTER

Mission Evolution



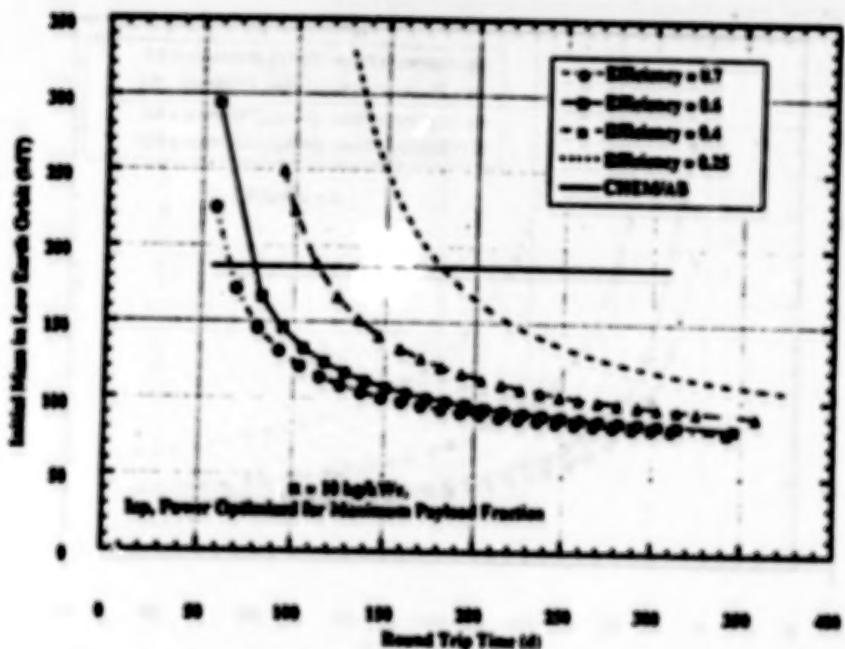
ADVANCED SPACE ANALYSIS OFFICE

Cases Considered

- Orbital Transfer
 - Lunar Cargo - $\Delta V = 8$ km/s
 - LEO = 500 km, Lunar Orbit = 100 km
 - 10,20 kg/kWe
 - 58 MT payload outbound, return empty
 - Power, Isp optimized for maximum payload fraction
- Planetary Cargo
 - Mars Cargo - 800 day one-way, including spirals
 - 10 kg/kWe
 - Payloads ~ 100 - 200 MT
 - Power Optimized for fixed Efficiency, Isp
- Piloted Planetary
 - Piloted Mars Mission
 - Opposition Class - 30 day stay time - 500 day trip time
 - No crew on board during spiral escape, capture at Earth
 - Crew trip time = heliocentric time + stay time
 - 124 MT outbound, 40.3 MT inbound payload
 - 5 kg/kWe
 - Power Optimized for fixed Efficiency, Isp
 - Fixed Power (10 MWe) also examined

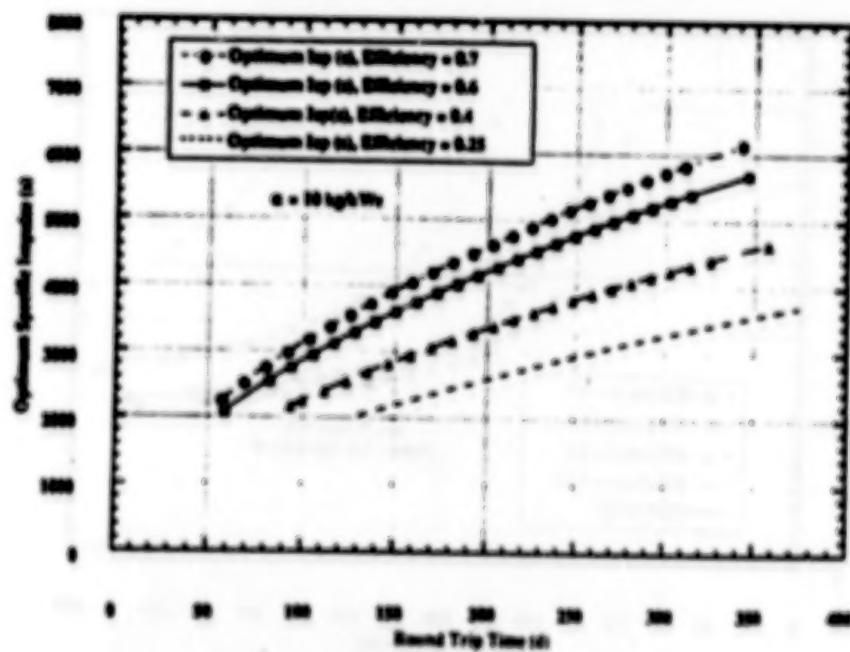
Lunar Cargo

**SENSITIVITY OF NEP TO EFFICIENCY
LUNAR CARGO MISSION - OPTIMIZED POWER, Isp**



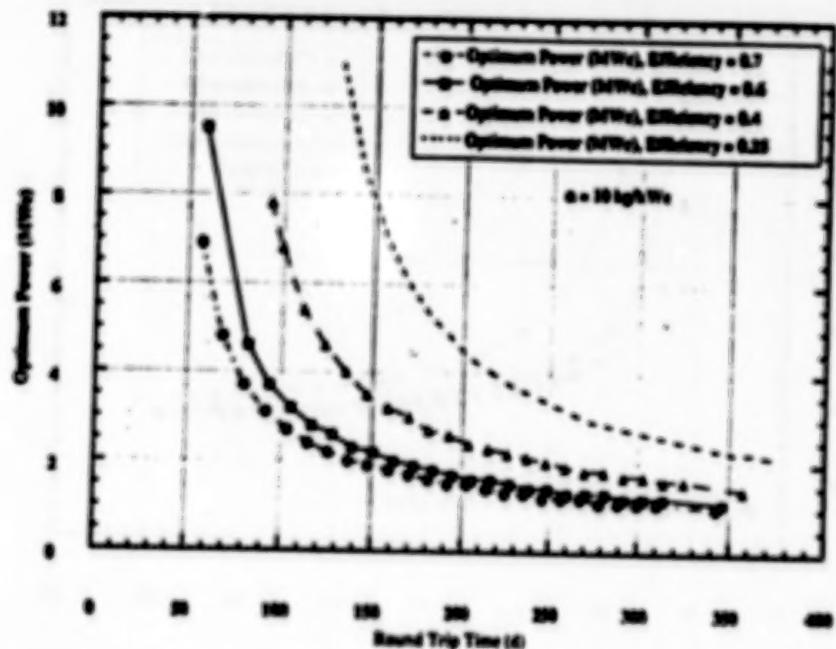
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**OPTIMIZED NEP Isp
LUNAR CARGO MISSION**



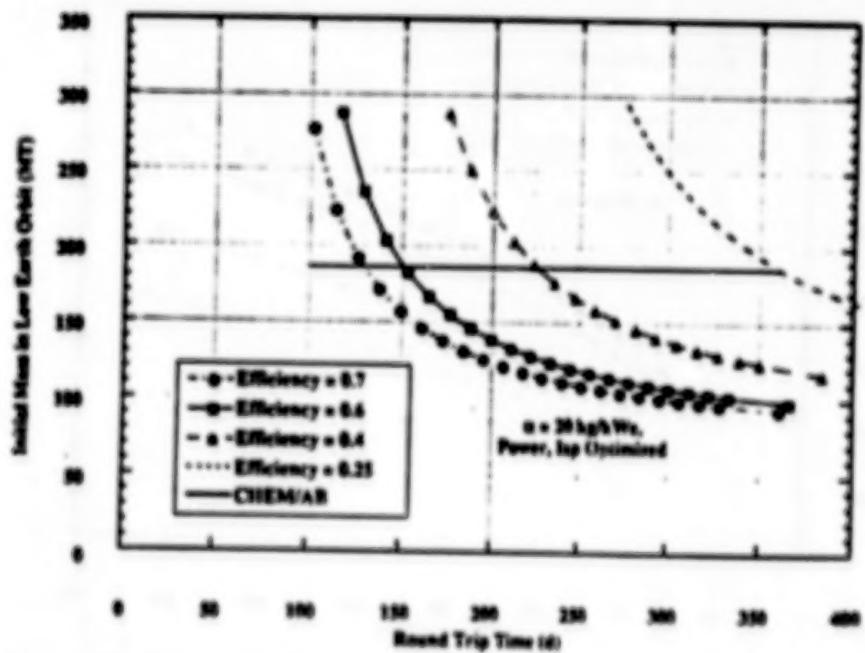
ADVANCED SPACE ANALYSIS OFFICE

OPTIMIZED NEP POWER LUNAR CARGO MISSION



ADVANCED SPACE ANALYSIS GROUP

SENSITIVITY OF NEP TO EFFICIENCY LUNAR CARGO MISSION - OPTIMIZED POWER, Isp

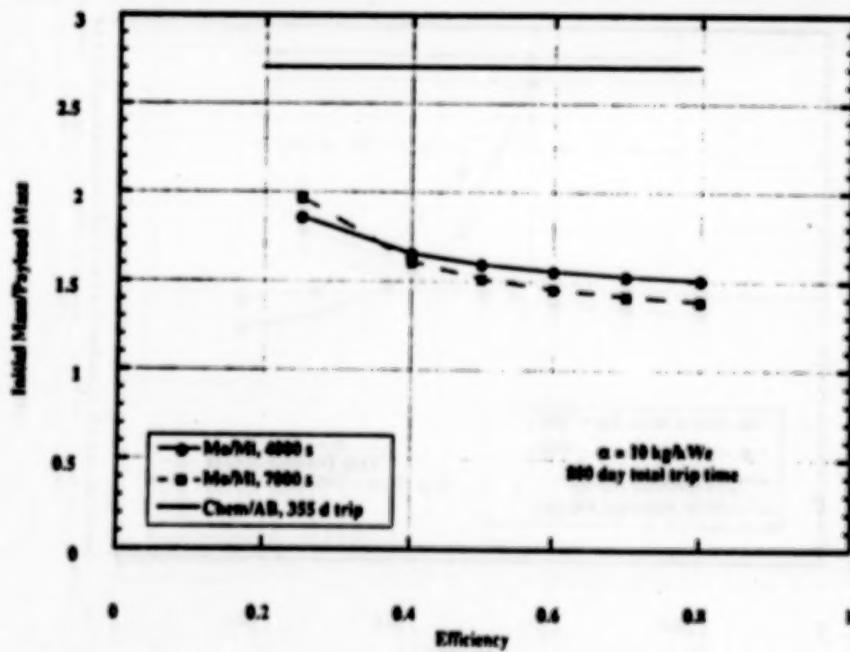


ADVANCED SPACE ANALYSIS GROUP

Mars Cargo

ADVANCED SPACE ANALYSIS CENTER

SENSITIVITY OF NEP TO EFFICIENCY, Isp MARS CARGO MISSION, VARYING POWER

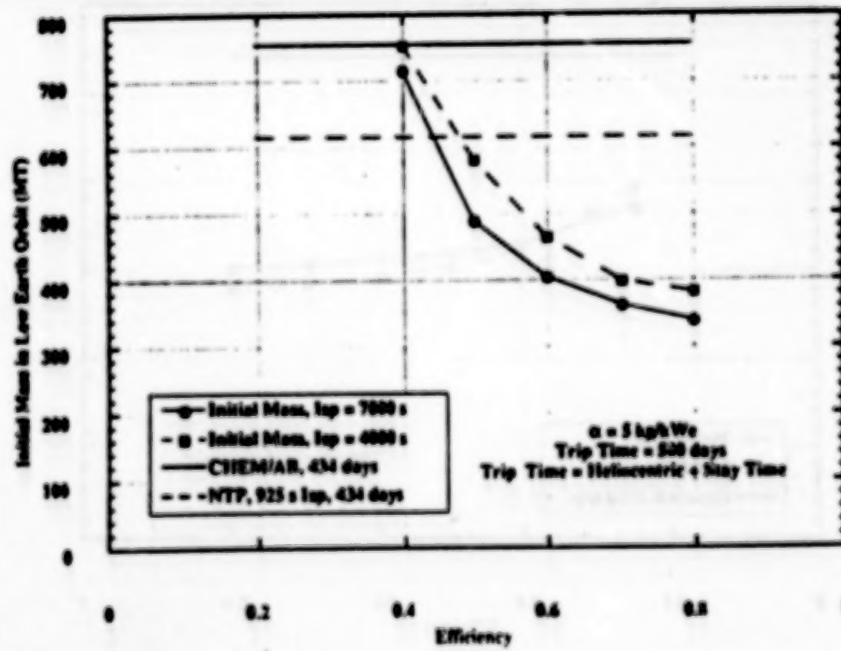


ADVANCED SPACE ANALYSIS CENTER

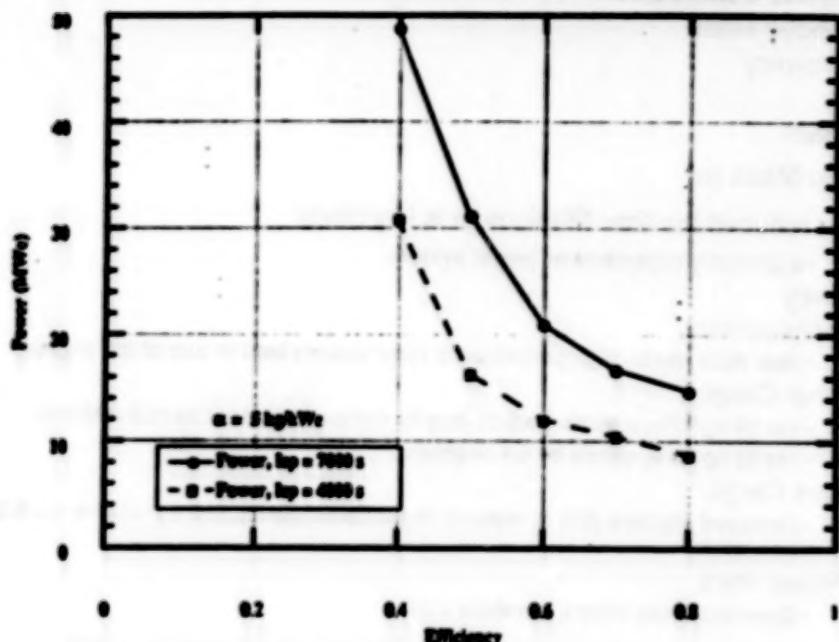
Mars Piloted

ADVANCED SPACE ANALYSIS GROUP

SENSITIVITY OF NEP TO EFFICIENCY, JSD PILOTED MARS MISSION, VARYING POWER

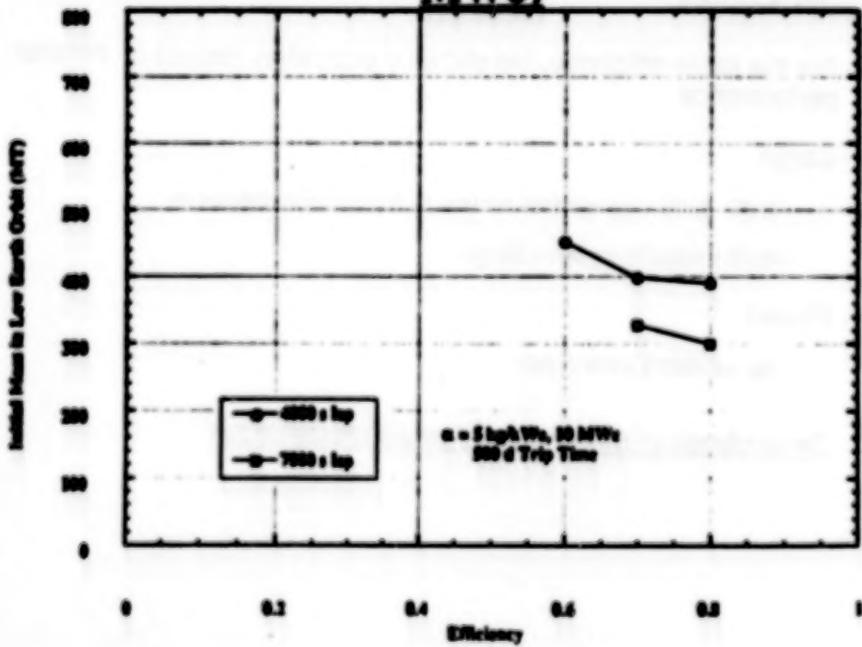


POWER REQUIREMENTS PILOTED MARS MISSION



ADVANCED SPACE ANALYSIS OFFICE

SENSITIVITY OF NEP TO EFFICIENCY, JSD PILOTED MARS MISSION, FIXED POWER (10 MWe)



ADVANCED SPACE ANALYSIS OFFICE

SUMMARY

- Parameters considered:

- Specific Mass
- Efficiency
- Isp
- Power

- Specific Mass (α)

- For reduced trip time Missions, α is key driver
 - α primarily dependent on power system

- Efficiency

- Interplanetary

- Near term needs, high performance requirements lead to use of ion engine

- Lunar Cargo

- For 10 lightWe, η as low as 0.25 may be competitive with Chem/Aerobrake

- For 20 lightWe, η must be 0.4 or greater

- Mars Cargo

- Extended trip time (300 d) reduces impact of efficiency, Isp variations; $\eta > 0.25$ may be useful

- Piloted Mars

- Short trip times drive η to values > 0.5

- Sensitivity to η will be greater for higher values of specific mass

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SUMMARY (cont.)

- Specific Impulse

- For the same efficiency, Isp shows a secondary impact on mission performance

- Cargo

- 2000 - 5000 s Isp suitable for low ΔV Earth-orbital missions

- 4000 s suitable for Mars Cargo

- Piloted

- Isp ≥ 4000 s satisfactory

- Dependence of η upon Isp will affect choice of Isp

ADVANCED SPACE ANALYSIS OFFICE

NASA

LEWIS RESEARCH CENTER

OPTIMIZED NEP Isp
LUNAR CARGO MISSION

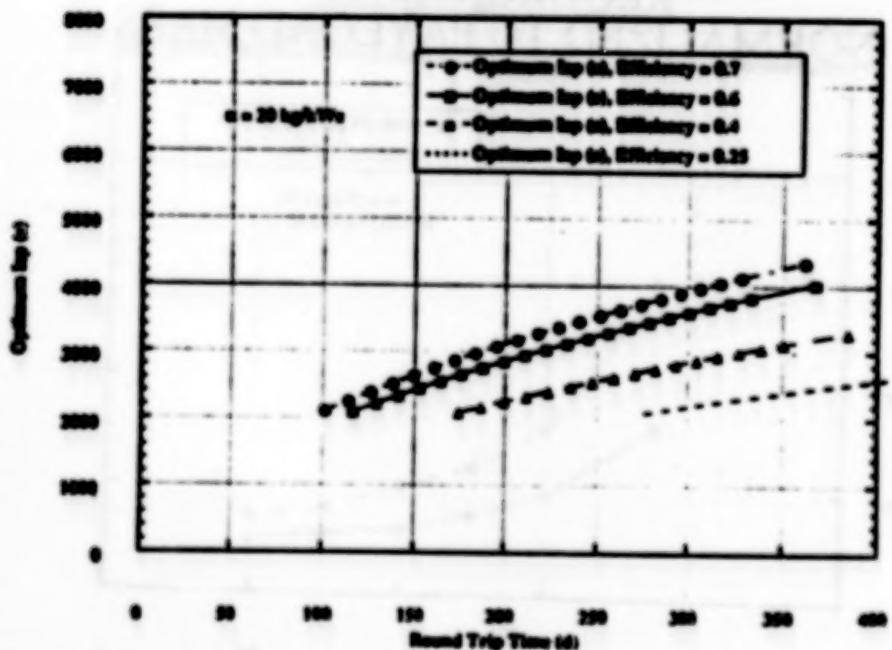
APPENDIX

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NASA

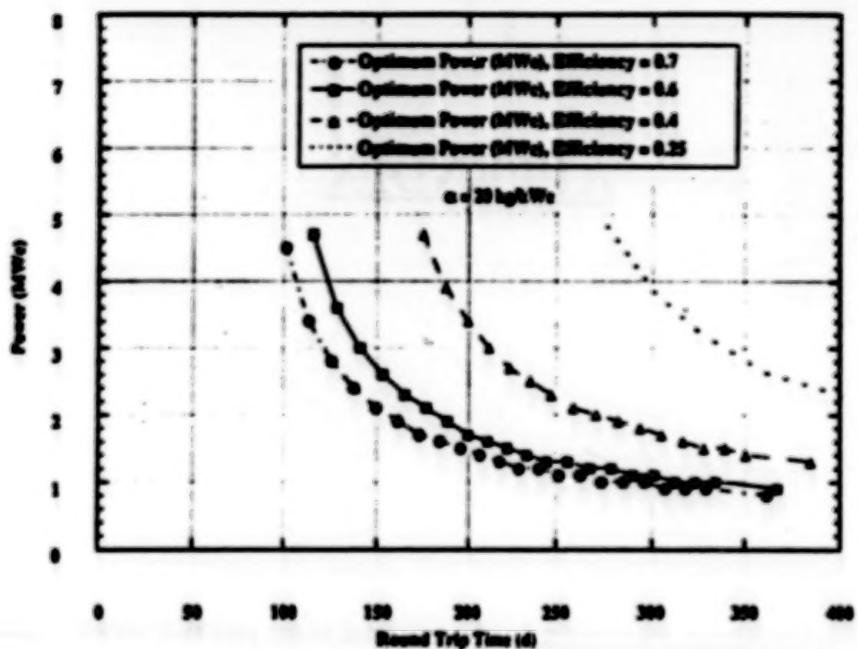
LEWIS RESEARCH CENTER

OPTIMIZED NEP Isp LUNAR CARGO MISSION



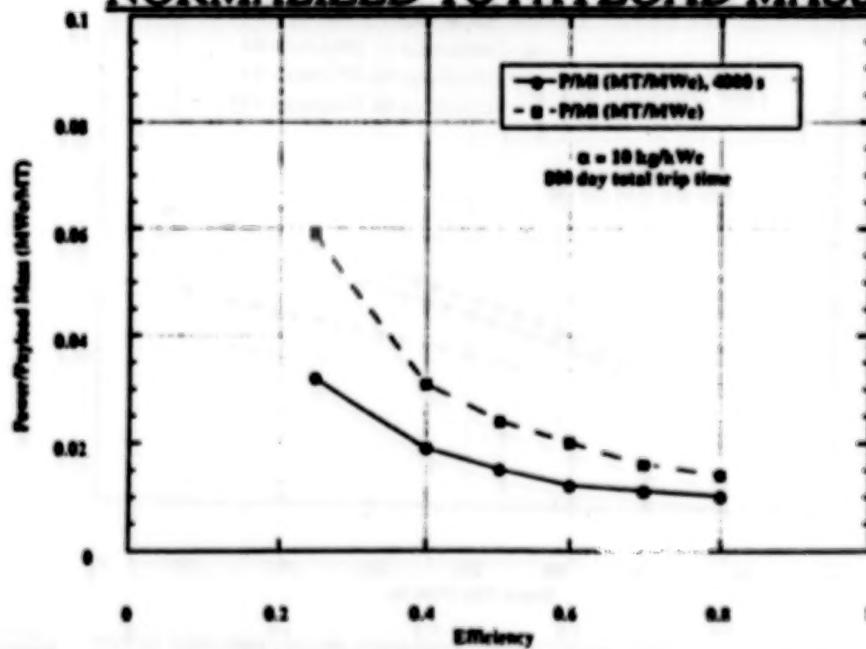
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OPTIMIZED NEP POWER LUNAR CARGO MISSION



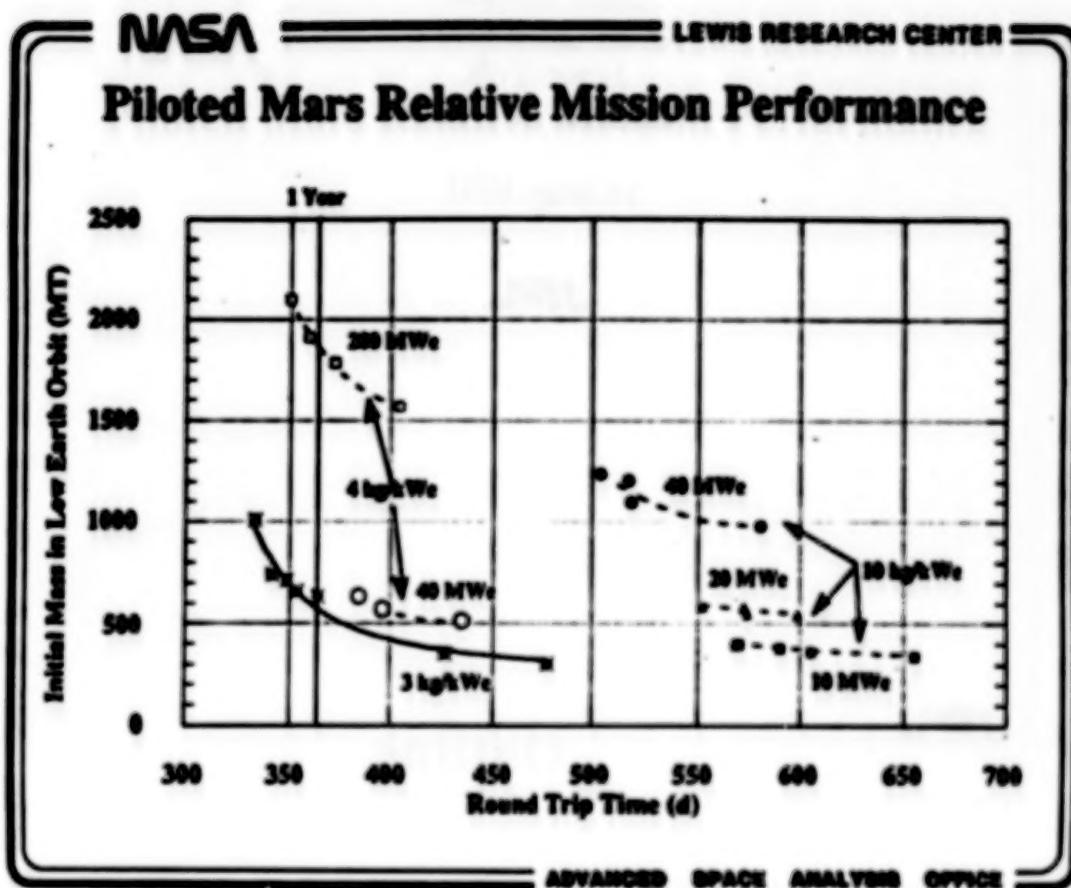
ADVANCED SPACE ARCHITECTURE OFFICE

MARS CARGO MISSION POWER REQUIREMENTS NORMALIZED TO PAYLOAD MASS



AIAA-89-0543-CP-1000

JPL to Mars and return from Mars



52-20
40048

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Appendix E

: P-17

The MPD Thruster Program at JPL

John Barnett
Keith Goodfellow
James Polk
Thomas Pivirotto

JJ574453

11

16 May 1991

JPL

JPL

Outline

THE SEI CONTEXT

CRITICAL ISSUES OF MPD THRUSTER DESIGN

THE MPD THRUSTER PROGRAM AT JPL

The SEI Context

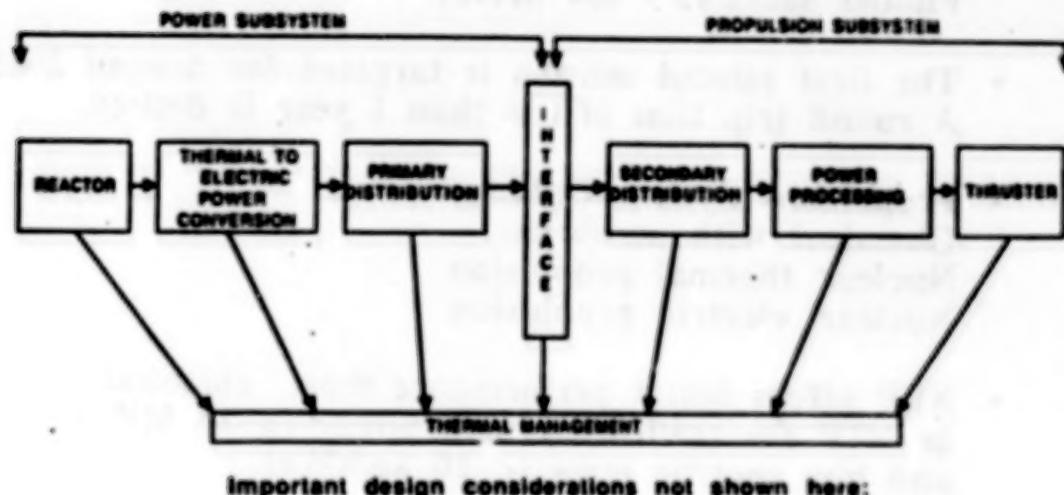
- **Missions:**
Robotic planetary exploration (100 - 500 kW_e)
Lunar and Mars Cargo (1 - 5 MWe)
Piloted Mars (5 - 40+ MWe)
- **The first piloted mission is targeted for around 2015.**
A round trip time of less than 1 year is desired.
- **Propulsion System Options:**
Chemical with aerobrake
Nuclear thermal propulsion
Nuclear electric propulsion
- **NEP offers better performance than chemical or NTP for sufficiently high power (> 10 MWe) and low specific mass (< 10 kg/kWe)**
- **The NTP lobby, bolstered by the NERVA experience, is strong. The nuclear propulsion program has so far been arbitrarily weighted toward NTP.**

The Nuclear Electric Propulsion System

- **The NEP System includes:**
Nuclear reactor
Power conversion
Power management and distribution
Power processing
Thruster
Thermal management
- **Although electric thruster funding has been anemic for decades, funding of other essential technologies is also low or absent.**

JPL

SCHEMATIC OF POWER AND PROPULSION SUBSYSTEMS



Important design considerations not shown here:

Shielding
Structure
Propellant Handling
Gimbals

JPL Some Electric Thruster Options

- Electric thruster options include:
 - Deflagration
 - ECR
 - ICR
 - Ion
 - MPD
 - Pulsed inductive
 - Pulsed plasmoid
 - "Variable Isp"
- Ion and MPD thrusters are leaders due to their developmental heritage. The ion engine is efficient, but has a relatively low thrust density and has been developed primarily at ≤ 10 kW. The MPD thruster is simpler in design and has a higher thrust density, but has not demonstrated efficient performance with the propellants normally considered. Neither device has demonstrated the required lifetime.

JPL

Critical Issues of MPD Thruster Development

GOAL: On a five-year time scale, demonstrate that performance required for SEI applications can be achieved or downselect to another thruster or propulsion system.

CRITICAL ISSUES: SYSTEM LEVEL

ISSUE: Definition of operational requirements

REQUIREMENT: Specification of characteristics of an MPD thruster-based propulsion system that beats the performance of competing systems for SEI missions (e.g. specific impulse, efficiency, specific mass, system power)

STATUS: Poor definition of SEI missions, requirements

APPROACH: Trade studies (including mix and match studies of MPD thruster with other sub-system options; pulsed vs. steady state operation; reliability analysis)

JPL

Critical Issues of MPD Thruster Development (Cont'd)

ISSUE: Thruster-spacecraft interactions

REQUIREMENT: Understanding of effects on spacecraft of MPD thruster, including mechanical, thermal and electrical interfaces; dynamic effects; exhaust plume-spacecraft interactions (including contamination from propellant and erosion products); and thruster-thruster interactions

STATUS: Poor understanding of these topics

APPROACH: Analysis and design studies; supporting experimental verification. A flight demonstration is essential.

**Critical Issues of
MPD Thruster Development (Cont'd)****ISSUE: Operating power level****REQUIREMENT: Megawatts per thruster****STATUS: Up to 300 kW (US); up to 800 kW (GE);
MW level (claimed by USSR) in steady state. Multi-MW
achieved in millisecond pulses.****APPROACH: Facilities-limited issue. US has taken an
"evolutionary" approach to high power, steady state
operation (versus an Edisonian approach).****ISSUE: Specific impulse****REQUIREMENT: 3000 to 8000 s, depending on mission****STATUS: Required range achieved for low (<100 kW) power
steady state and MW-level pulsed operation****APPROACH: Maintain desired range while increasing power,
efficiency and lifetime. Focus on electrode geometry and
propellant selection, injection.****Critical Issues of
MPD Thruster Development (Cont'd)****CRITICAL ISSUES: COMPONENT LEVEL****ISSUE: Efficiency (Electric input to directed kinetic)****REQUIREMENT: > 50%****STATUS: 40% on H₂; nearly 70% on Li reported at
about 5000 s. (These data for pulsed or low power devices.)****APPROACH: Analyses and experiments focused on
the design parameters electrode geometry; magnetic
field strength and geometry (self or applied); propellant
(substance, flow rate, injection geometry); total power
level; and physical scale****ISSUE: Lifetime****REQUIREMENT: 10E9 N-s (on the order of 6 months,
100 N)****STATUS: 10E6 N-s demonstrated steady-state (500 hr,
33 kW)****APPROACH: Analyses and experiments focused on the
parameters total power; component operating temperature
and materials; electrode geometry and current density;
magnetic field strength and configuration; propellant**

JPL

**Critical Issues of
MPD Thruster Development (Cont'd)**

ISSUE: Thermal management

REQUIREMENT: Remove MW of thermal power from engine at temperatures of 1400 K to 2300 K.

STATUS: Technology appears in hand; need for design and experimental verification.

APPROACH: Self-radiating grids, pumped Li loop, composite fins

ISSUE: Facility requirements

REQUIREMENT: 10E7 l/s pumping speed (for 6 g/s Ar at 10 E-4 torr). Must be dedicated for life tests, able to accommodate thermal load.

STATUS: Existing US facilities have pumping speeds at least an order of magnitude too small, are very expensive, and are not dedicated to MPD thruster development.

APPROACH: Establish facility requirements for various developmental tasks; use existing facilities to generate data supporting the cost of a dedicated full-up facility. Explore alternate pumping schemes. Establish pulsed-steady state correspondence.

JPL

Summary of Critical Issues

<u>ISSUE</u>	<u>A FOCUS OF JPL's MPD PROGRAM</u>
Definition of operational requirements	
Thruster-spacecraft interactions	X
Operating power level	
Specific Impulse	
Efficiency	
Lifetime	X
Thermal management	X
Facility requirements	X

JPL The MPD Thruster Program at JPL: Programmatic Overview

- **Funded under NASA RTOP**
- **FY91 Level of Effort: 3.5 WY**
- **Personnel:** **T. Pivirotto (RTOP Manager)**
K. Goodfellow
J. Polk
W. Thogmartin
- **Facility:** **3000 square feet**
Five test chambers
Three 60 kW welding power supplies

JPL

The MPD Thruster Program at JPL

EMPHASIS: **Engine component lifetime and thermal management.**

APPROACH: **Theoretical and experimental specification of thermal loads and failure mechanisms**

SPECIFIC ELEMENTS:

- **Testbed MPD engine**
- **High-current cathode test facility**
- **Component thermal modelling**
- **Alkali metal propellant studies**

JPL

Radiation-cooled MPD Thruster

GOAL: Develop a testbed engine to study thruster thermal behavior and life-limiting mechanisms.

PROGRESS:

- Stable operation demonstrated for
 - Power: 3-50 kW
 - Applied B-field: 0-1360 G
 - Propellant/Flow rate: Argon 0.07-0.43 g/s
 - Ammonia 0.07-0.30 g/s
- Graphite and tungsten nozzles tested
- Two cathode geometries tested

JPL

Radiation-cooled MPD Thruster

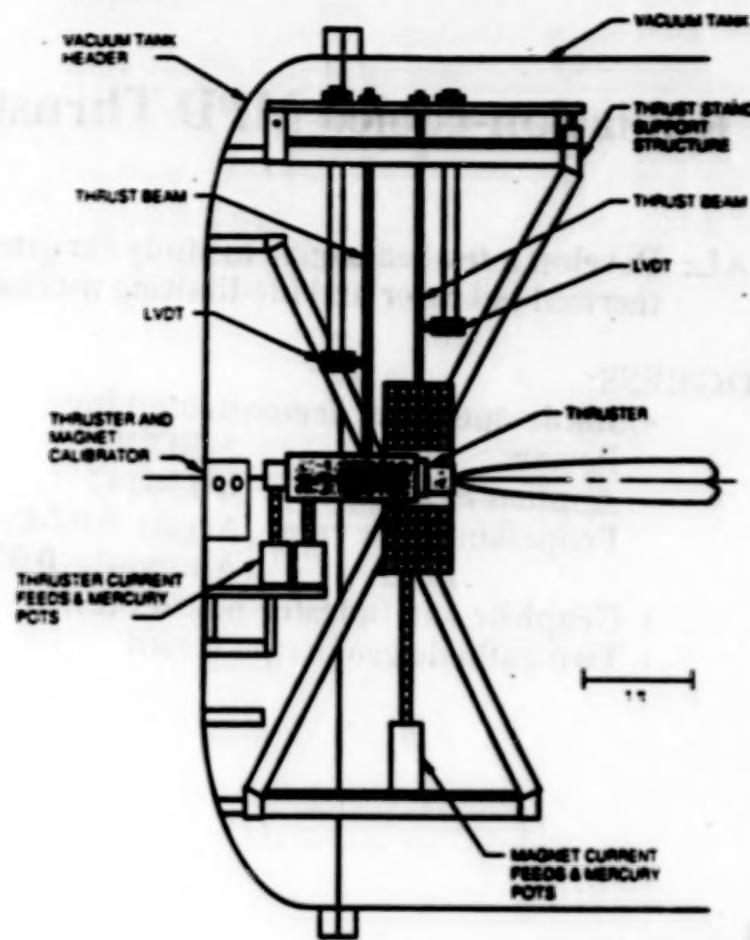
PROGRESS (cont.):

- Preliminary thrust data obtained
- Alternate pumping scheme verified

SUBSEQUENT MILESTONES:

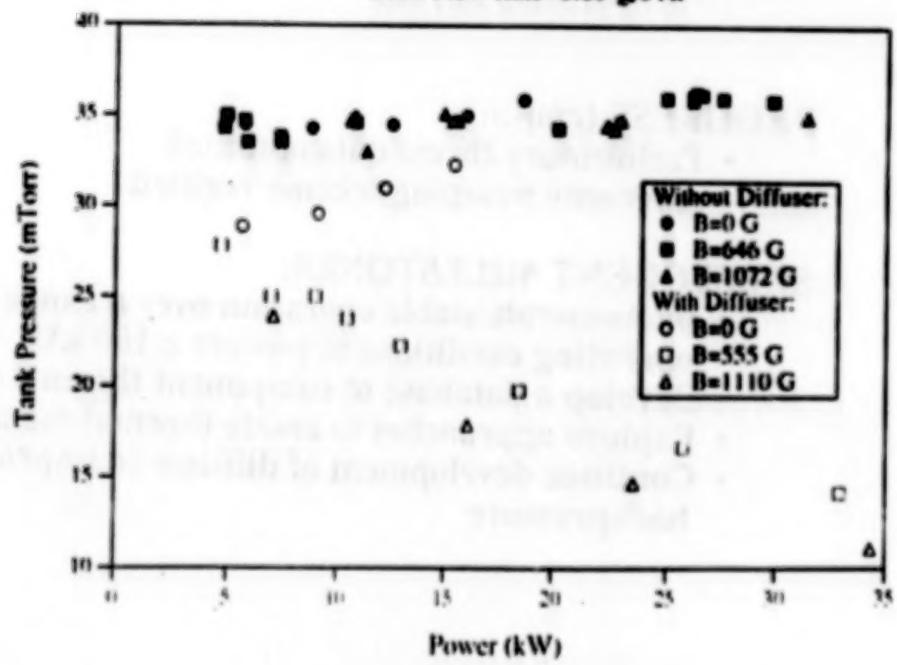
- Demonstrate stable operation over a range of operating conditions at powers ≥ 100 kW
- Develop a database of component thermal data
- Explore approaches to anode thermal management
- Continue development of diffuser to improve backpressure

JPL



JPL

DIFFUSER EFFECT ON TANK PRESSURE
Mass Flow Rate=0.09 g/s Ar



JPL

High-Current Cathode Test Facility

GOAL: Supply thermal data for modelling effort and develop long-lived cathodes for high current applications.

PROGRESS:

- Testing requirements defined
- Vacuum facility obtained

JPL

High-Current Cathode Test Facility

PLANNED ACTIVITIES:

- Cathode surface temperature measurements
- Characterization of near-cathode plasma environment
- Erosion measurements and alternate materials evaluation
- Cathode endurance tests

JPL

Thruster Component Thermal Modelling

GOAL: Develop capability to predict engine component temperatures for given geometries and operating conditions.

PROGRESS:

- Commercial FEM software procured
- Simple cathode sheath model completed
- Developing cathode thermal model

JPL

Thruster Component Thermal Modelling

SUBSEQUENT MILESTONES:

- Complete component thermal models
- Refine electrode sheath models to provide boundary conditions
- Couple component and sheath models with a plasma flow model--potential for JPL-LeRC collaboration
- Experimentally confirm model predictions

JPL

Alkali Metal Propellant Studies

GOAL: Evaluate benefits of alkali metal propellants

CURRENT ACTIVITY:

- Performing preliminary assessment of systems-level impact of alkali metal propellants
- Estimating cost of performing alkali metal thruster tests at the JPL Edwards Facility

JPL

Alkali Metal Propellant Studies

POTENTIAL FUTURE EMPHASIS:

- Develop facility and expertise in alkali metal handling
- Study effect of propellant on cathode work function
- Verify performance improvements
- Define contamination potential

LLNL - Contributions to MPD Thrusters for SEI

MPD Thruster Technology Workshop
NASA, Washington, D.C.

LH075075


E. Bickford Hooper

May 16, 1991

LLNL CAN CONTRIBUTE TO MPD THRUSTER DEVELOPMENT FOR SEI



Near-Term:

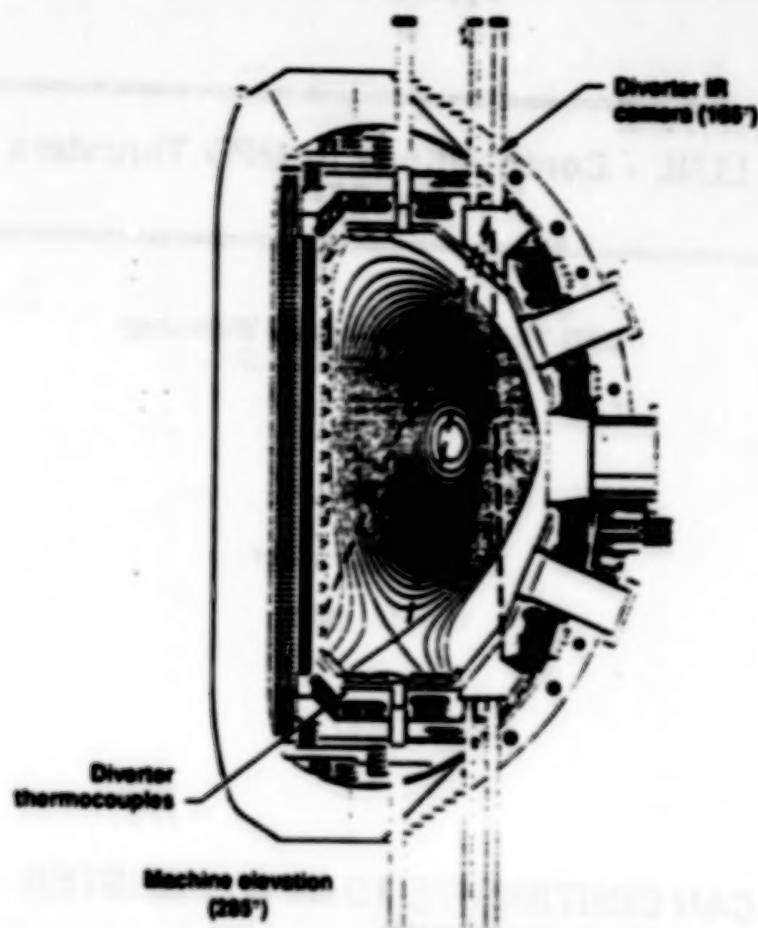
- Modeling of MHD characteristics using the TRAC code, which has been benchmarked against the RACE experiment at LLNL
- Application of tokamak "divertor" physics
 - Modeling of atomic - plasma interactions (gas penetration, ionization, excitation, radiation) using the Brahma and Degas codes
 - Measurements of MHD and atomic effects
 - Modeling of erosion/sputtering and redeposition of refractory materials
- Remote measurements of density, temperature, magnetic field using fusion diagnostics

These contributions can best be made in collaboration with ongoing experiments

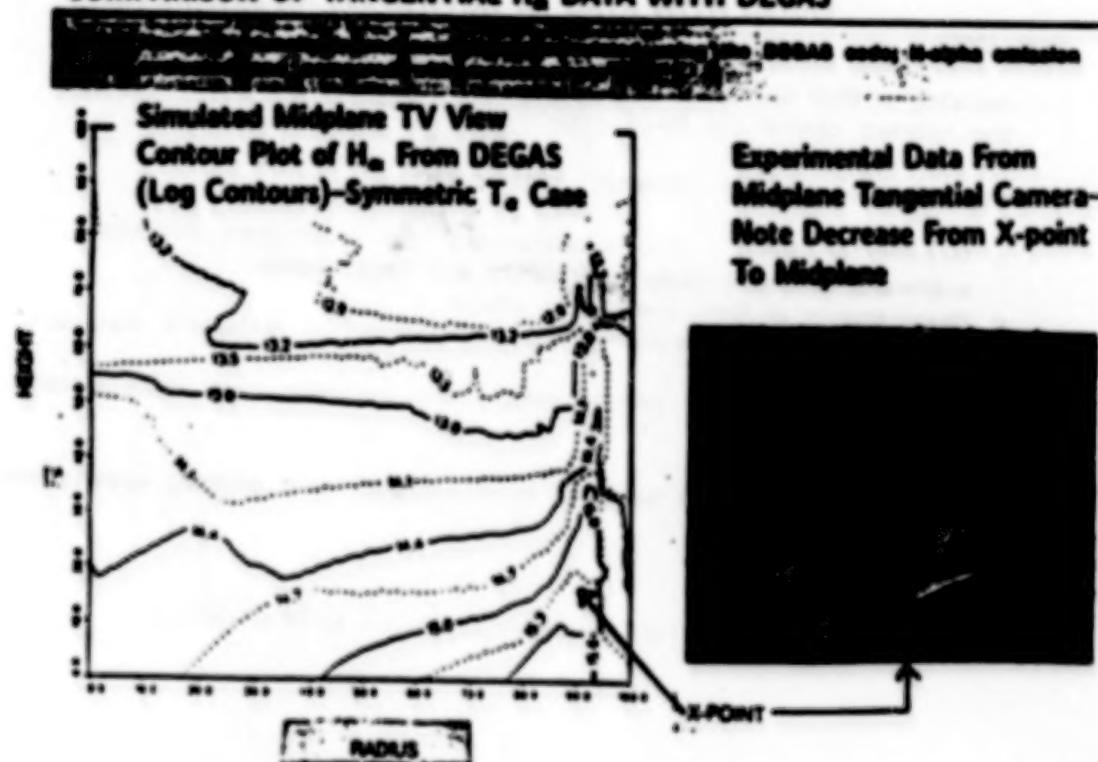
Long-Term:

- High power tests for lifetime validation using the MFTF-B facility

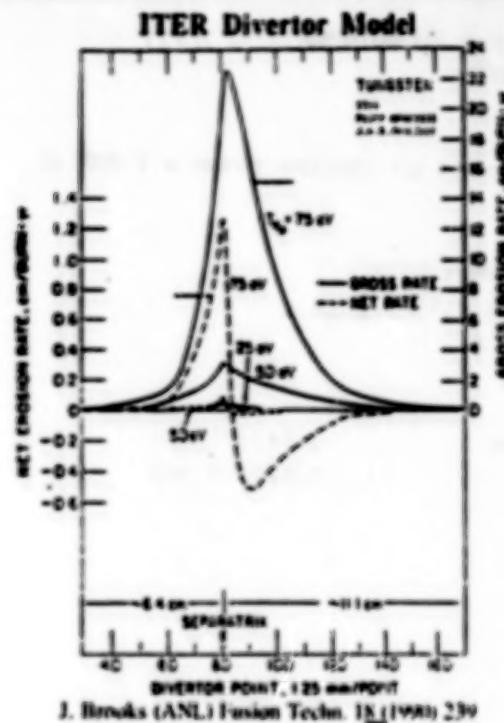
Divertor IR camera



COMPARISON OF TANGENTIAL H_α DATA WITH DEGAS



The MFE community has developed considerable expertise in plasma-induced erosion/redeposition

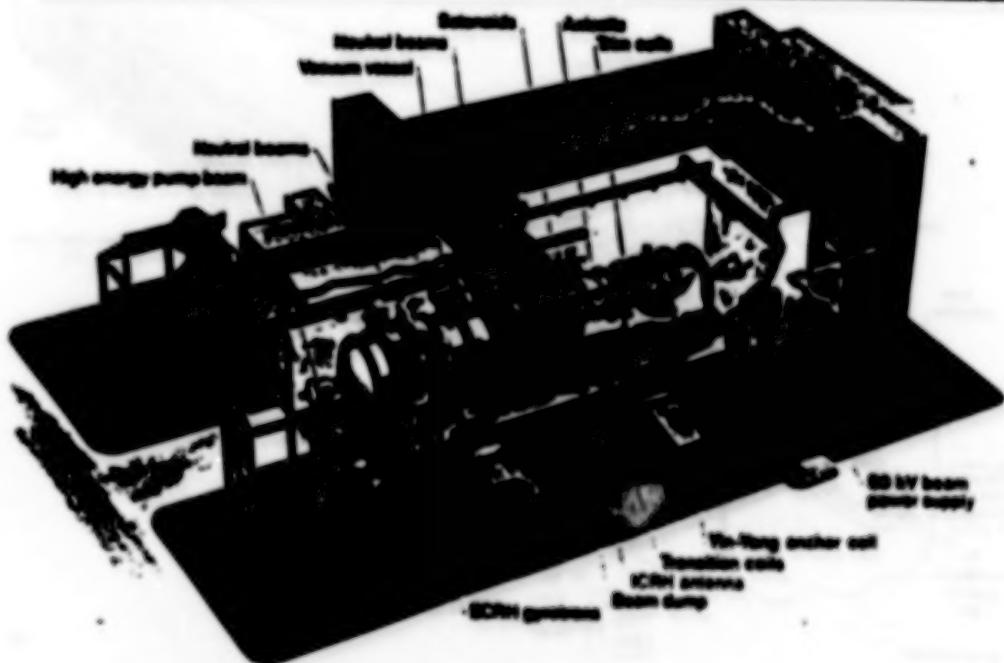


- Computer codes such as REDEP are used to predict net erosion including redeposition effects

- These calculations are benchmarked against measurements in tokamaks and off-line simulation facilities

THE MFTF-B

13



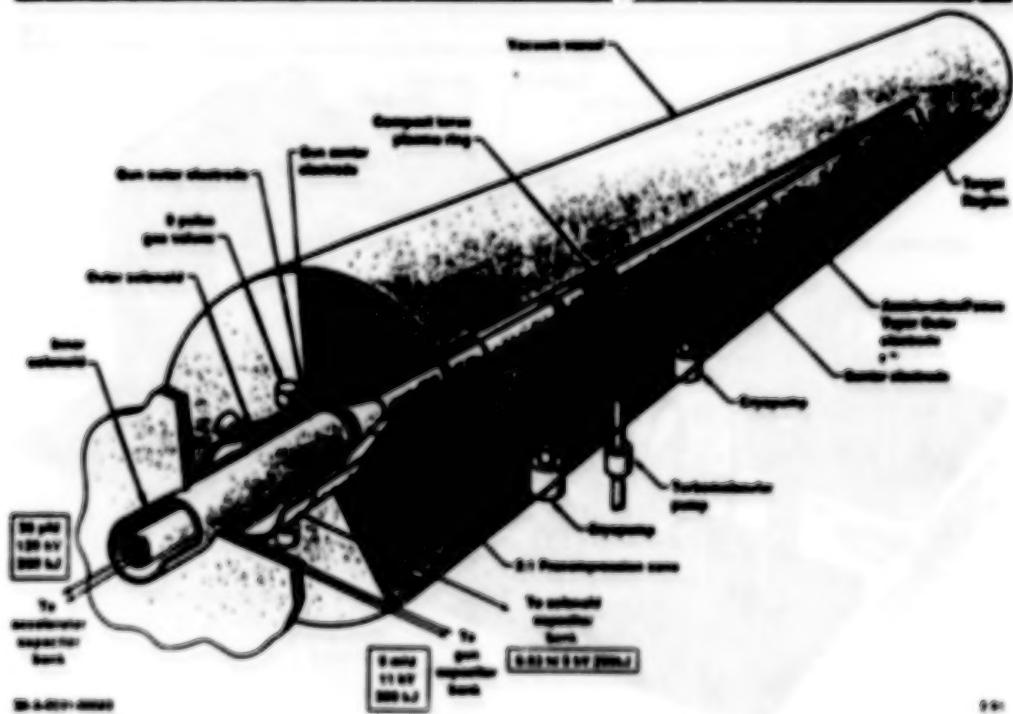
PROPOSED THRUSTER LIFETIME TEST FACILITY

- MFTF-B: Size 35' diameter by 200' long
1000 m³ of cryopanels
11 kW of LHe cooling available for pumping
500 kW closed loop LN₂ system
250 MVA power line
- Example test conditions: mass flow = 0.4 g/s (thruster power = 1 MW at
 $v = 7 \times 10^4$ m/s)

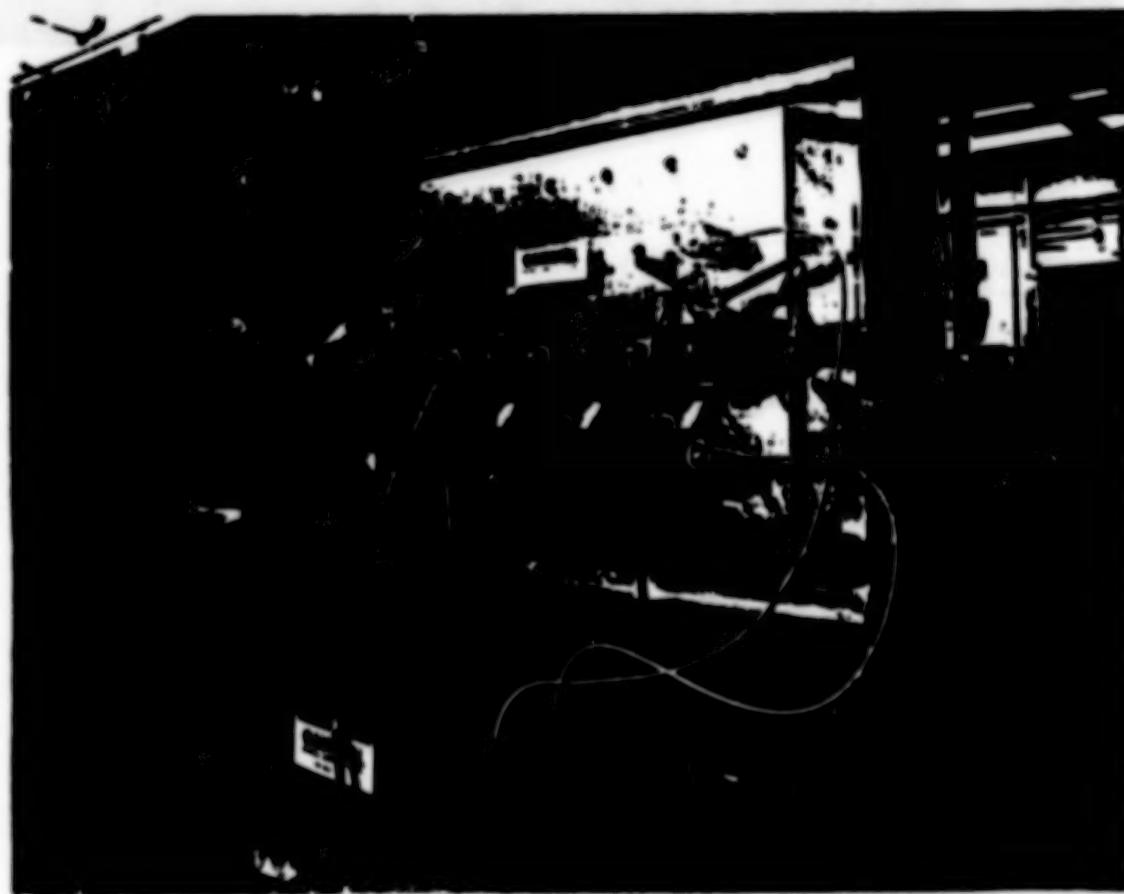
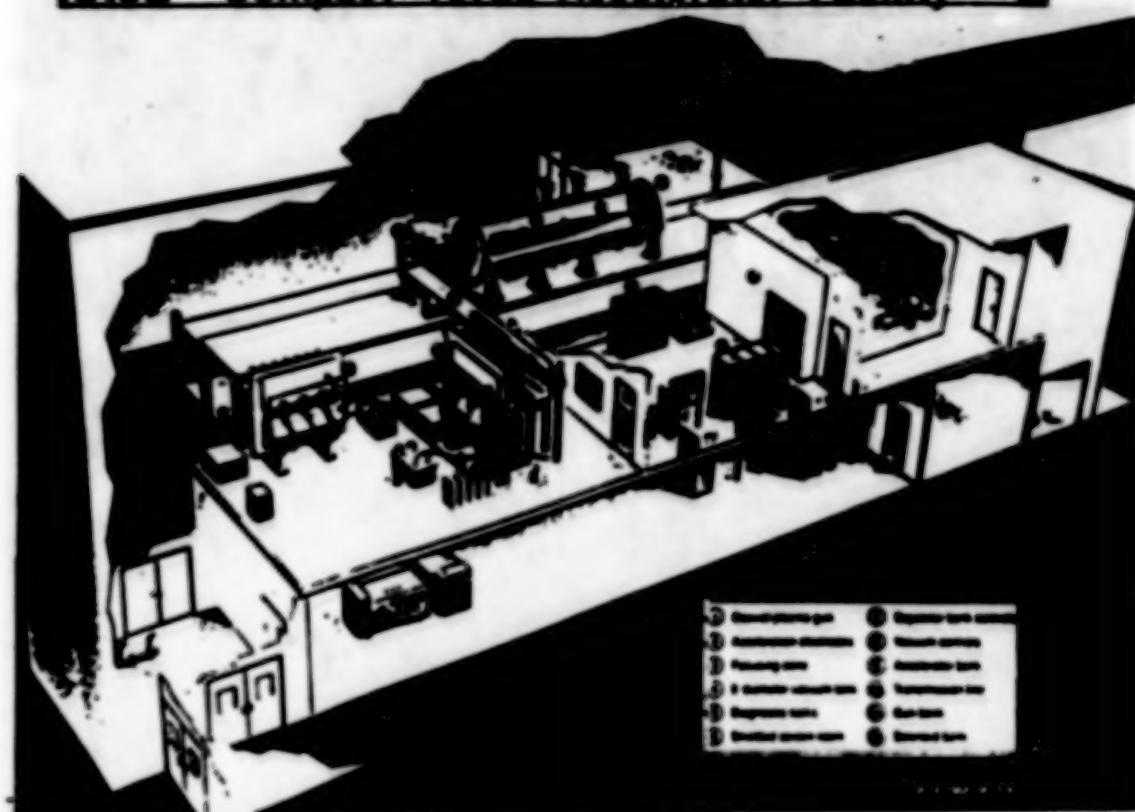
Pumping speed 67×10^6 liters/s, D₂
 $67 \times 10^6 (4/A)^{1/2}$ liters/s,
 Mass A

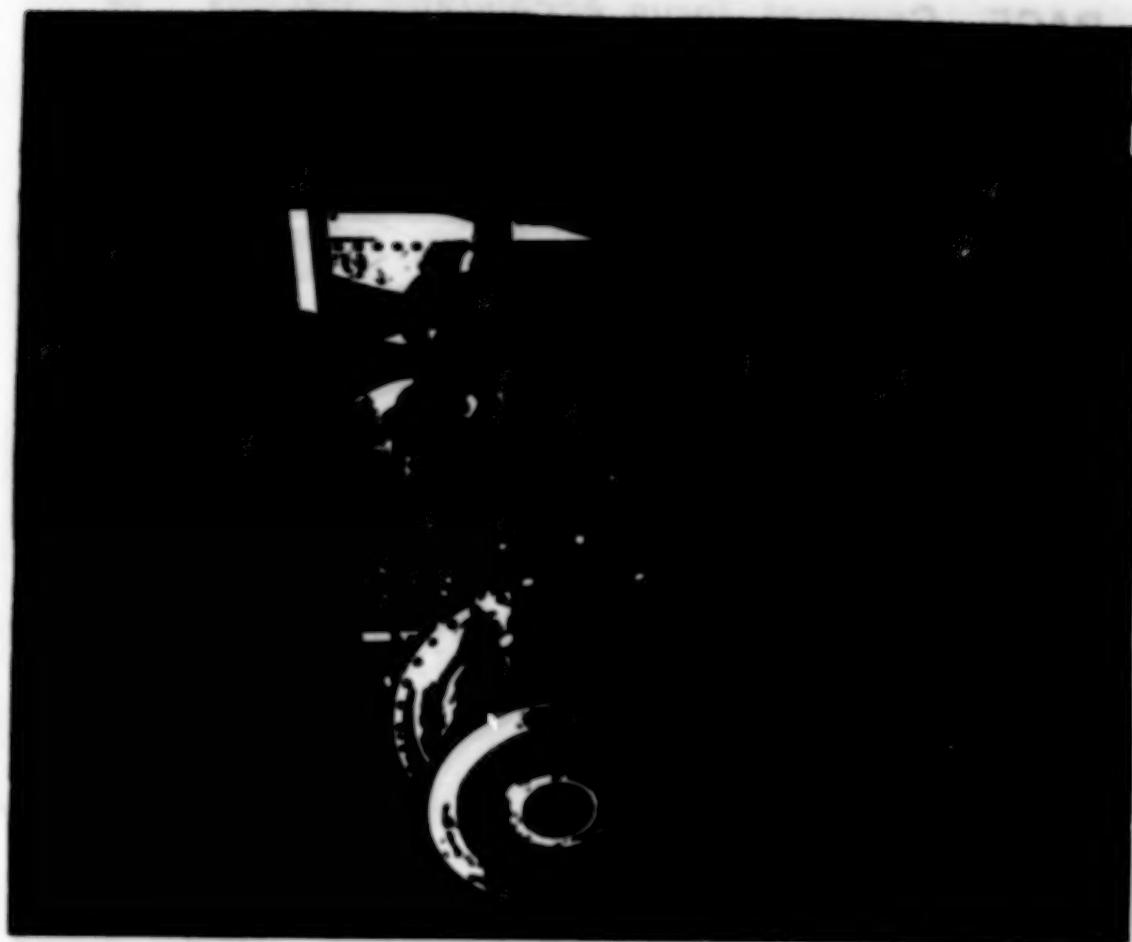
Equilibrium pressure

The RACE experiment test the basic concepts of ring acceleration



RACE Compact Torus Accelerator Facility





RACE program summary

Goals	Predictions		Results to Date
Demonstrate ring formation	Magnetic energy	2-40 kJ	2-10 kJ
	Mass	5-500 microgram	5-500 microgram
	Length	70 cm	50-100 cm
Demonstrate acceleration in linear coaxial system	Velocity	$1-2 \times 10^5$ cm/sec	$1-3 \times 10^5$ cm/sec
	Energy	Up to 100 kJ	50-60 kJ
	Efficiency	0.4	0.3-0.4
	$U_{beam}/U_{magnetic}$	5	10
Demonstrate ring focusing	R_{beam}/R_{beam}	1.5	1.5

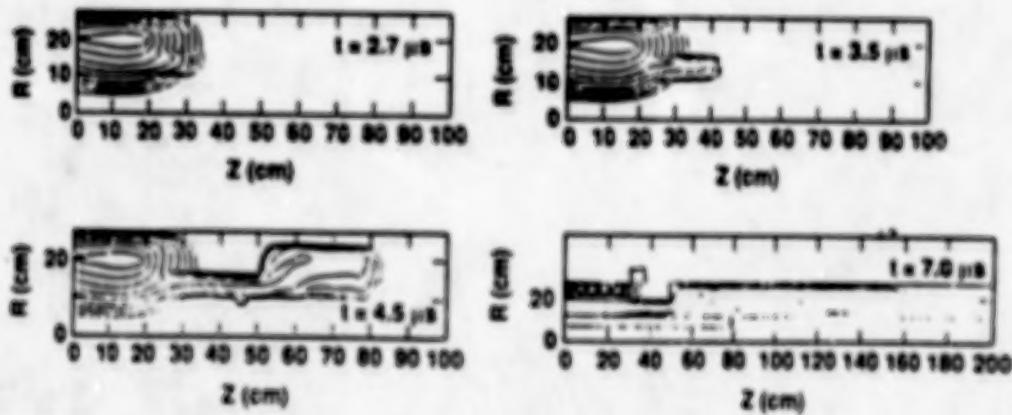
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Comparison of race data of plasma ring formation with the HAM 2D-MHD code

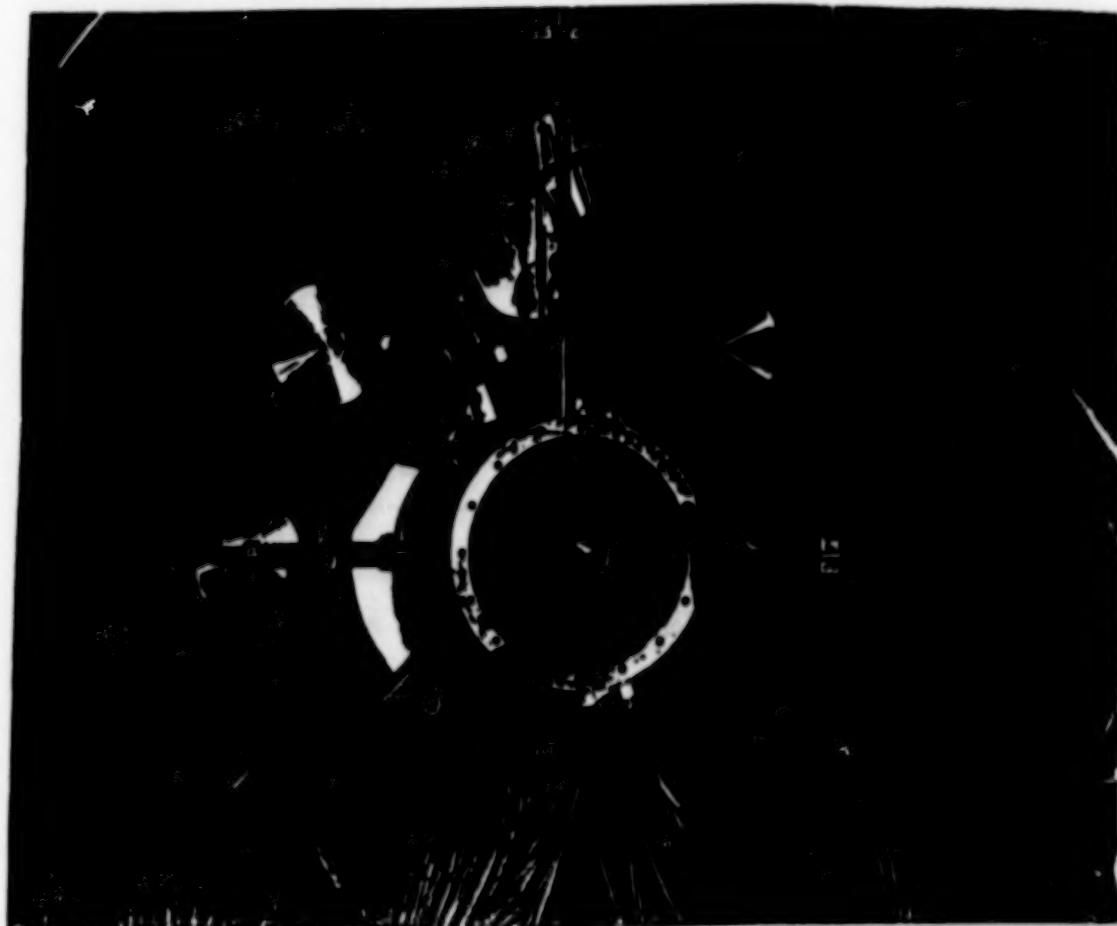
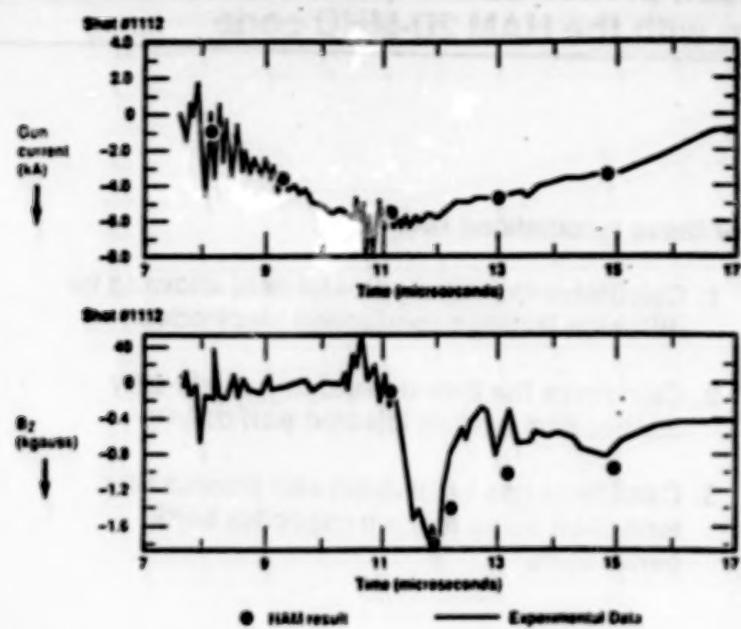
For these calculations HAM:

1. Calculates the initial poloidal field allowing for diffusion through conducting electrodes
2. Calculates the time-dependent gas density distribution from an injected puff of gas
3. Calculates gas breakdown and plasma ring formation using the gun capacitor bank parameters

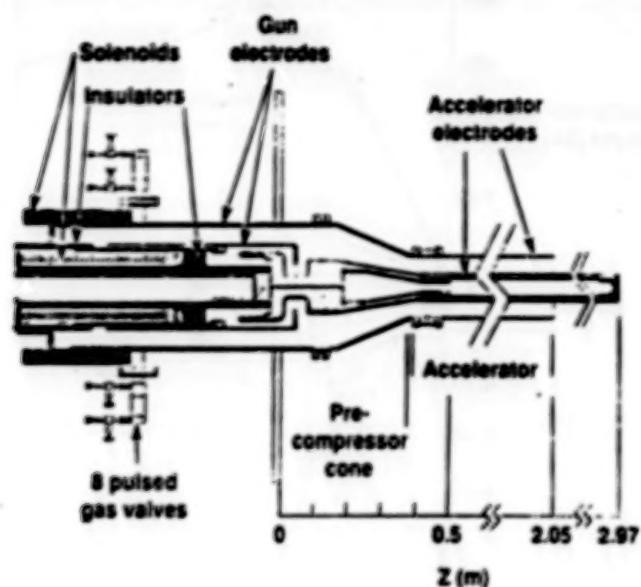
Flux contours for HAM simulation



2D MHD simulations agree with the experimentally observed current

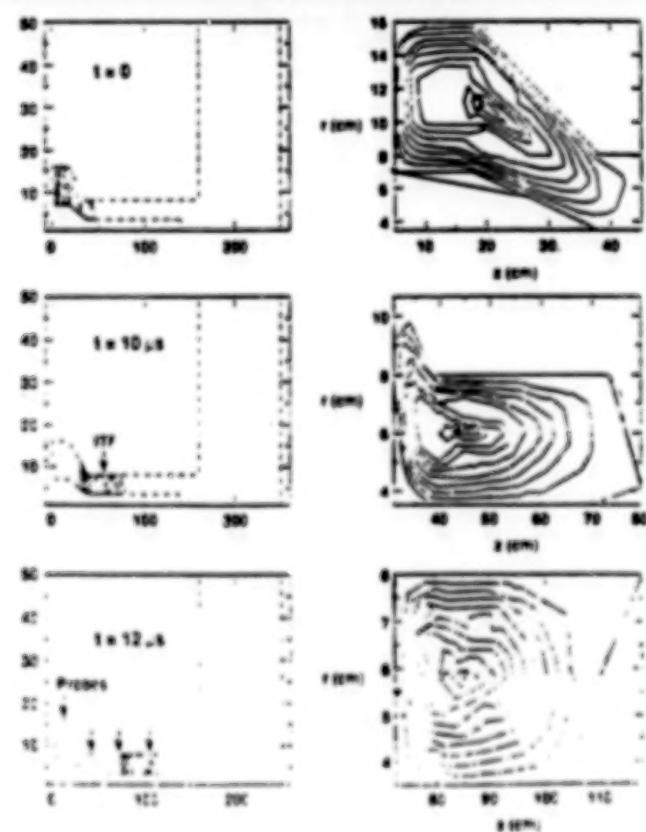


RACE, the Ring ACcelerator Experiment, configuration during precompressor tests

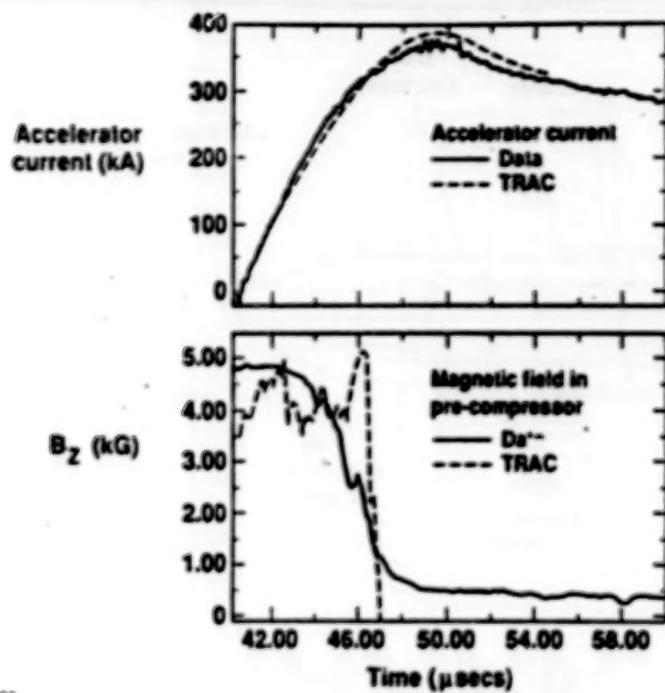


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TRAC (Two-dimentional Ring Acceleration Code) has been used to model the RACE pre-compressor

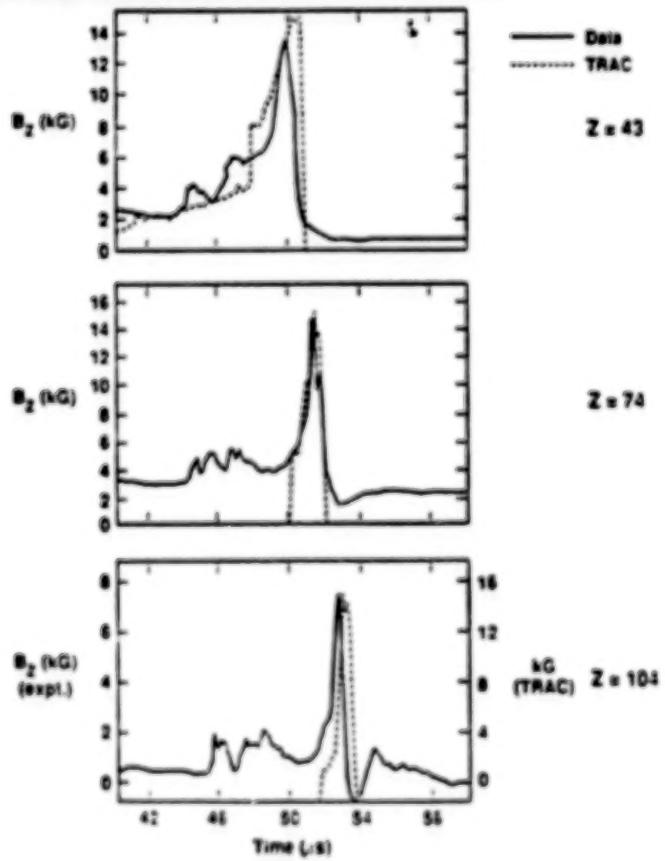


Comparison of trac with shot 5554 ($V_{ACC} = 80$ kV)



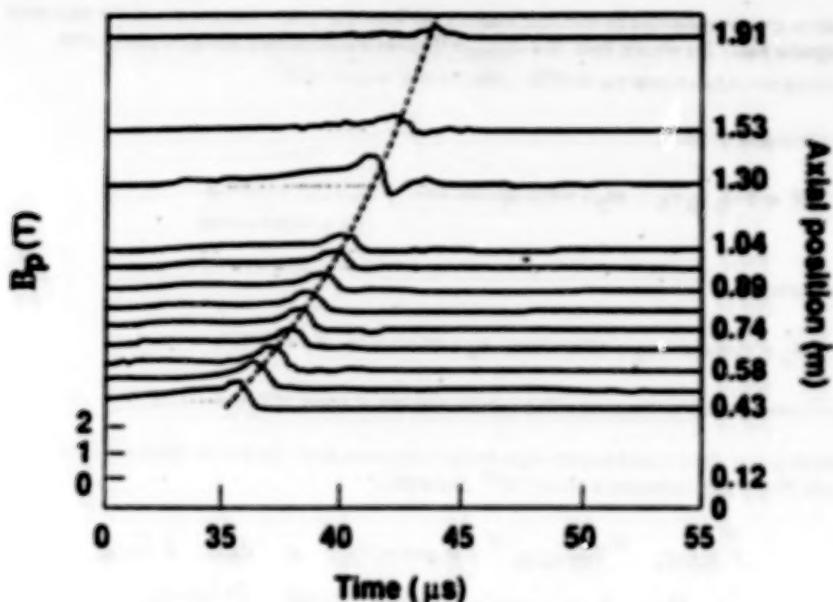
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Comparison with shot 5554 cont'd B_z vs. t at different locations in straight section

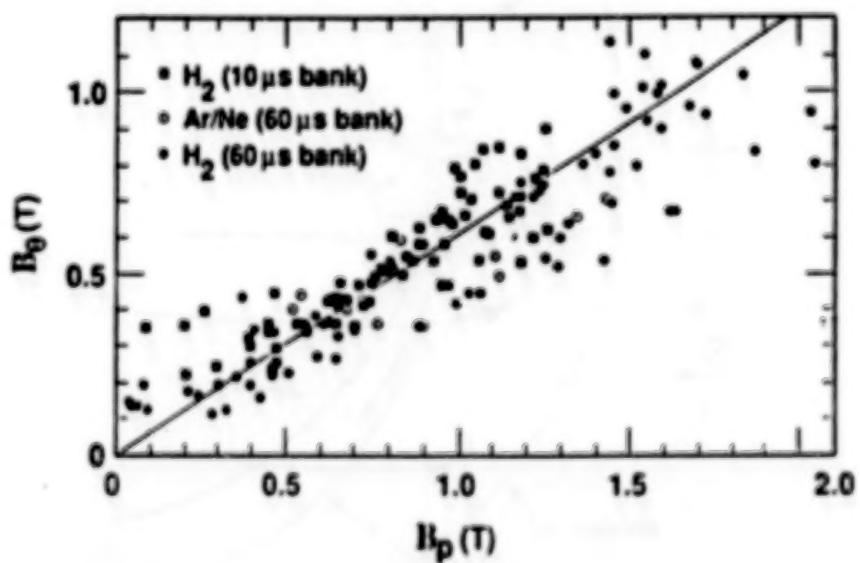


20-A-0495-0124

CT accelerates and is stable after precompression



CT in quasi-static pressure balance during compression in conical electrodes



An Alternate Application of MPD Arc Sources: Plasma "Tethers" for Tapping the Solar Wind EMF for Power > 10 MW

Plasma plumes generated by MPD arc sources can extend of order 1000 km across the solar wind magnetic field. The electric field, $E = n_{\text{plasma}} \times B$, gives a voltage drop along the plume, and currents are induced as in the AMPTE artificial comet experiments.

The available power is:

$$P = 2 M_p v_p v_A \quad M_p = \text{mass ejection rate} \quad v_p = \text{plume velocity.} \\ v_A = \text{Alfvén velocity}$$

An example:

$$M_p = 10 \text{ g/sec.}, \quad v_p = 60 \text{ km/sec.}, \quad v_A = 30 \text{ km/sec.}, \quad P = 100 \text{ MW}$$

The power could drive thrusters with a specific impulse of about 3000 sec.

A lunar power station could extract large amounts of power since there is unlimited available mass. The energy extracted is about 10^{18} Joules/Sec/G.

Plasma "Tethers" generate a bow shock
in the supersonic solar wind plasma

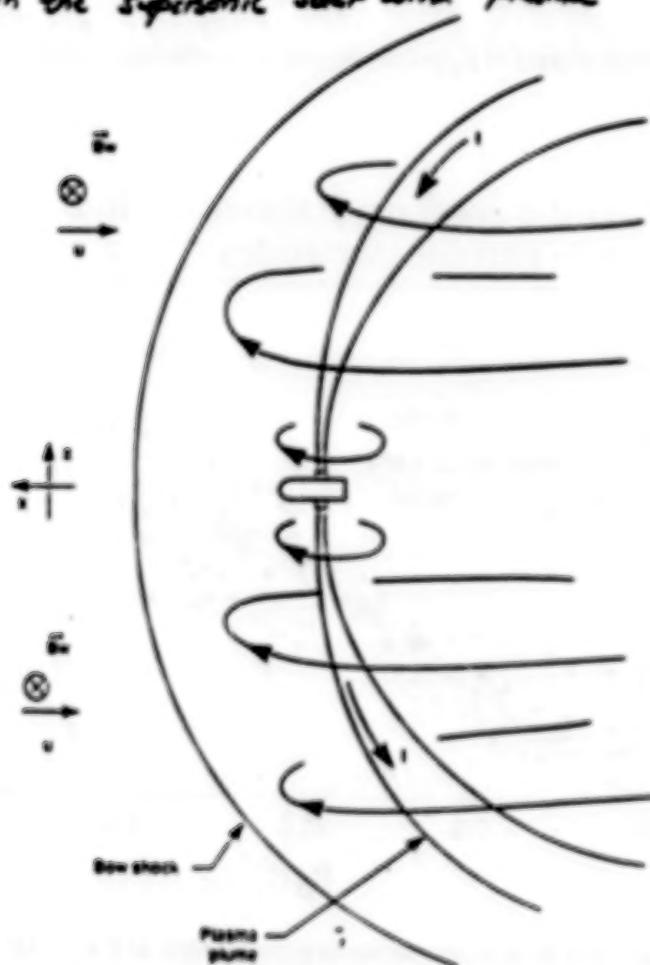


Figure 2

The plane in cross-section

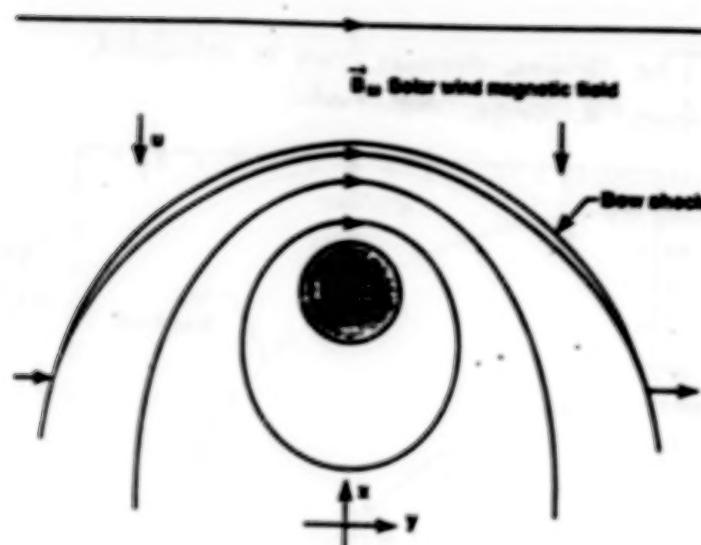


Figure 1

A conceptual solution for self-sustaining, plasma guns / thrusters

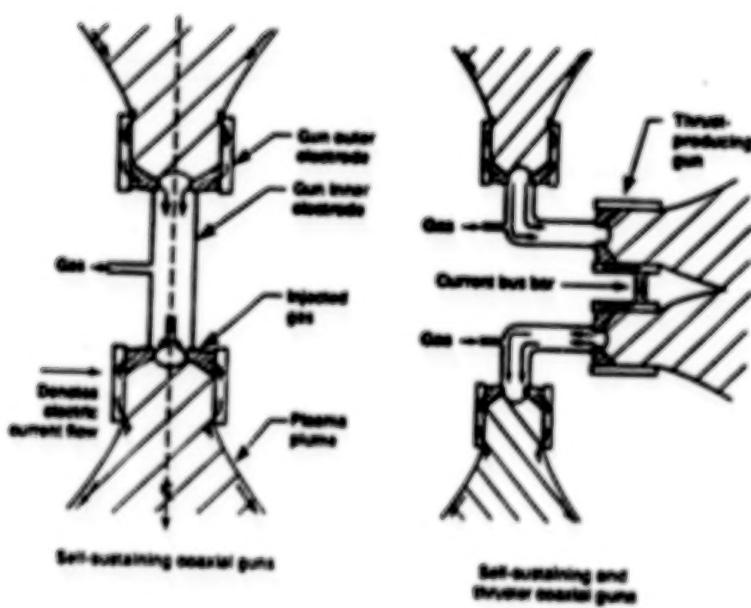
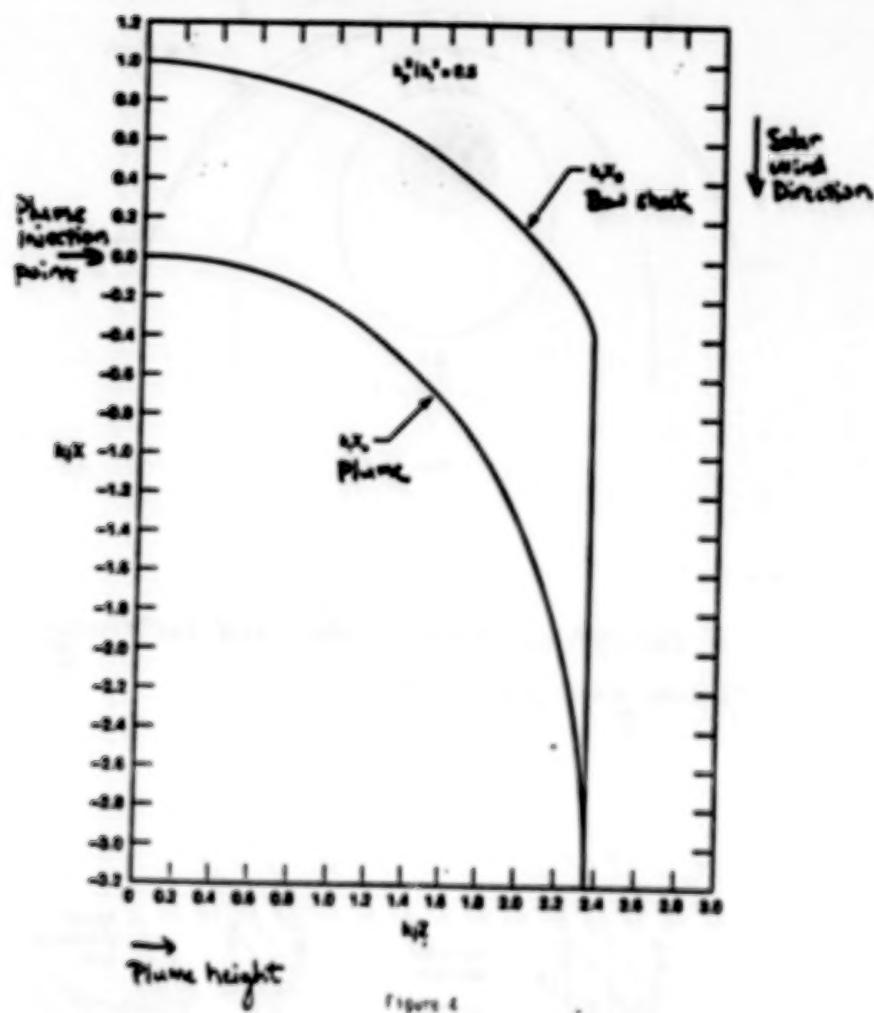


Figure 2

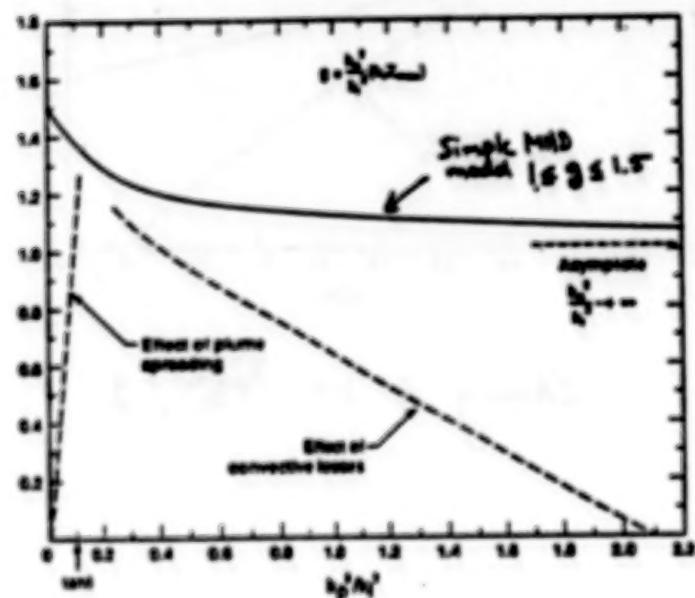
The plume dynamics can be calculated from a simple MHD model.



F-14

The Plume Power Extraction is
a function of the dimensionless ratio b_p/b_s

$$P = 2 \dot{M}_p V_p V_A g$$



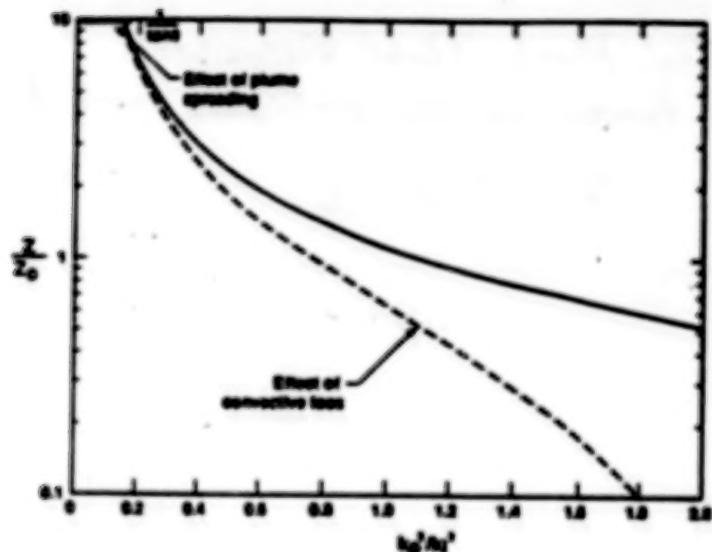
θ = plume divergence angle $\frac{b_p^2}{b_s^2} = \frac{\mu_0}{12} \frac{I^2}{\dot{M}_p V_p}$

Figure 5

60-0001-00714

The load impedance is a function of k_0^2/k_1^2 and is of order

$$Z \approx Z_0 = \frac{\mu_0 V_0}{4\pi} \quad V_0 = \text{Solar wind Alfvén velocity}$$



Choosing Z sets $k_0^2/k_1^2, j$

Figure 6

Conclusion: LLNL has extensive expertise in physics and technology relevant to MPD thruster development

Areas in which we could contribute include:

Modeling of atomic physics, plasma surface interactions and 2D MHD flows

Results from ongoing high-power plasma accelerator experiments (RACE)

Plasma diagnostics

High pumping speed test stand for lifetime validation studies (MFTF-B)

*E. 11-22
due 10/10/90
return 11/1*

Sy-20

Appendix G

N92-10048

*40050
P-13*



SPACE PROPULSION TECHNOLOGY DIVISION

NASA
Lewis Research Center

MPD THRUSTER TECHNOLOGY

ROGER M. MYERS

SVERDRUP TECHNOLOGY
NASA LEWIS RESEARCH CENTER

MAY 16, 1991

56005682



SPACE PROPULSION TECHNOLOGY DIVISION

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Lewis Research Center

IN-HOUSE PROGRAM OVERVIEW

- RE ESTABLISHED IN 1987
- FOCUSED ON STEADY-STATE THRUSTERS AT POWERS < 1 MW
- DEVELOPED PERFORMANCE MEASUREMENT AND DIAGNOSTICS TECHNOLOGIES FOR HIGH POWER THRUSTERS
- DEVELOPING MHD CODE
- GOALS ARE TO ESTABLISH
 - PERFORMANCE AND LIFE LIMITATIONS
 - INFLUENCE OF APPLIED FIELDS
 - PROPELLANT EFFECTS
 - SCALING LAWS



SPACE PROPULSION TECHNOLOGY DIVISION

NASA

MPD Thruster Technology

High Power MPD Thruster Test Stand

Power



• 0.50 MW

Thrust stand



• 0.1 to 4 N

Vacuum facility



• 0.1 g/s at 2×10^{-4} TORR

Data/control

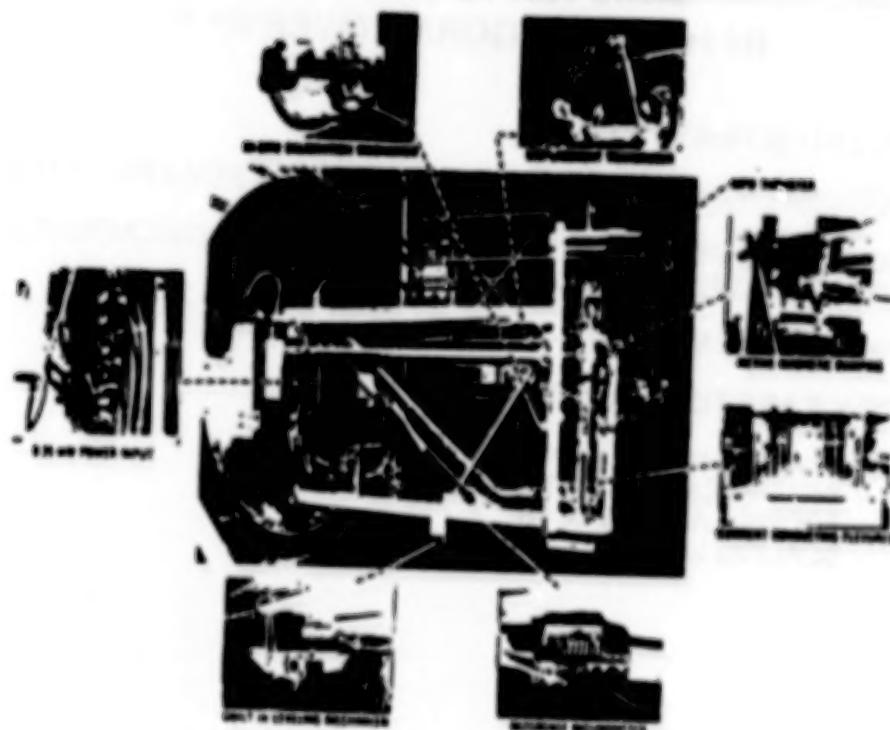


220 kW Thruster



08-01-0000

MPD THRUSTER TEST STAND



08-01-0000

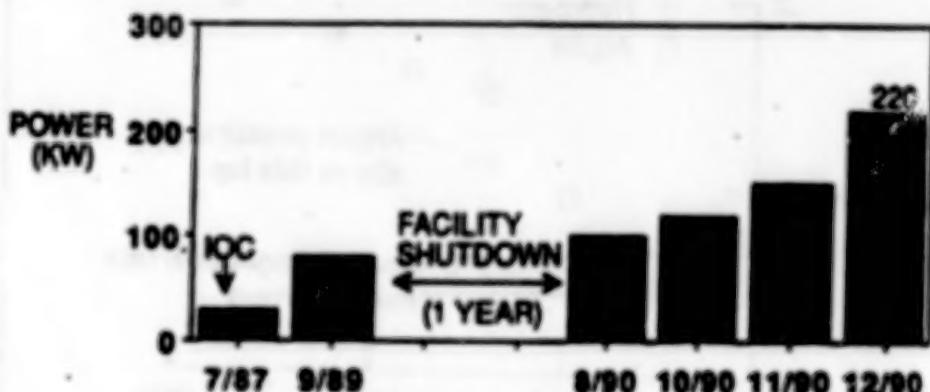


SPACE PROPULSION TECHNOLOGY DIVISION



HIGH POWER ELECTRIC PROPULSION (MPD)

DEMONSTRATED MPD THRUSTER POWER



DEMONSTRATED MPD THRUSTER POWER INCREASING RAPIDLY

SPACE PROPULSION TECHNOLOGY DIVISION

MPD Thruster Technology

Thruster Scaling and Materials Effects



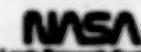
3 and 4 inch diameter anodes both 3 and 6 inches long

1 and 1 inch diameter cathodes

V and BeO-impregnated tungsten cathodes

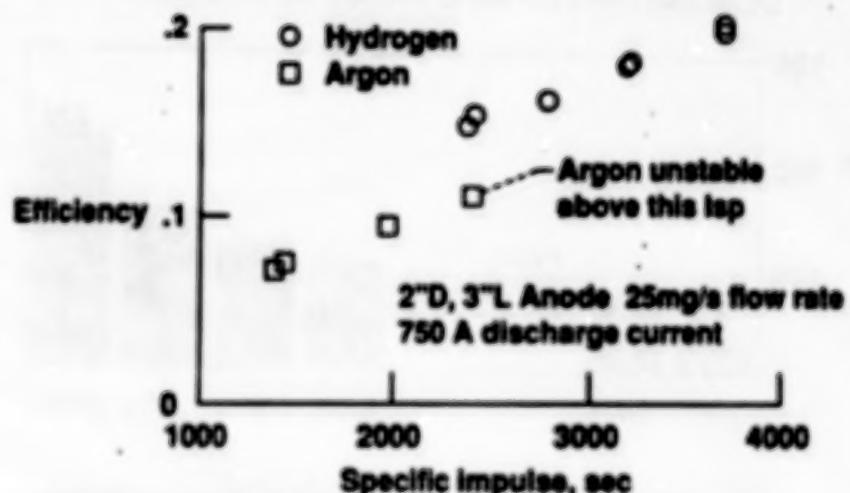


SPACE PROPULSION TECHNOLOGY DIVISION



MPD Thruster Technology

Performance Measured With Hydrogen and Argon



Performance dramatically improved with hydrogen

- Efficiency increased by 2X
- I_{SP} increased by 50%

CB-81-2402



SPACE PROPULSION TECHNOLOGY DIVISION



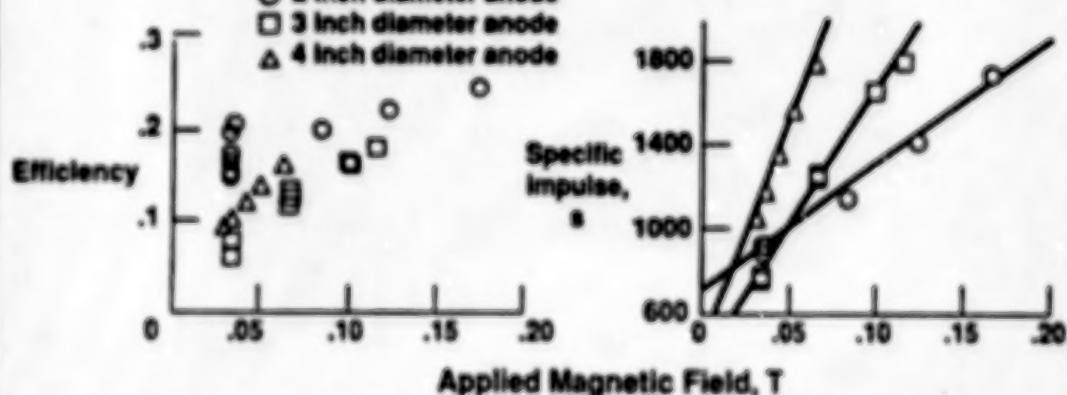
MPD Thruster Technology

Thruster Performance
Geometry and Applied Field Effects $J_d = 1000 \text{ A}$, $\dot{m} = 0.1 \text{ g/s}$ argon

○ 2 inch diameter anode

□ 3 inch diameter anode

△ 4 inch diameter anode



- Efficiency increases with applied field strength
- Specific impulse increases with both anode radius and applied field strength

CB-81-2402

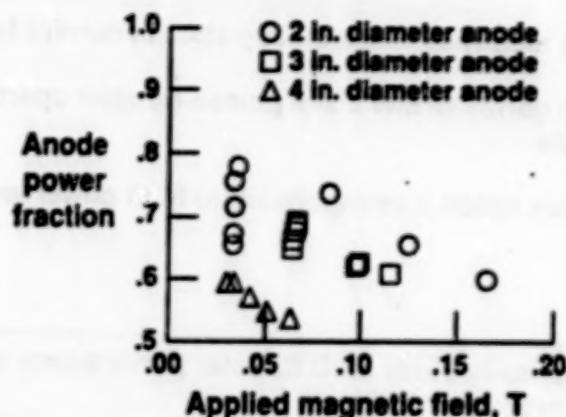


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MPD Thruster Technology

Anode Power Deposition Applied Field and Geometry Effects

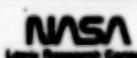


Increasing applied field strength and anode diameter decrease anode power fraction

CD-91-9422



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HIGH POWER ELECTRIC PROPULSION (MPD)

MPD THRUSTER HIGH CURRENT HOLLOW CATHODE TECHNOLOGY

High area emitter



Low area emitter



Three hollow cathode assemblies fabricated
and prepared for evaluation

CD-91-9115



SPACE PROPULSION TECHNOLOGY DIVISION



MPD Thruster Technology

Scaling Issues

- Megawatt class operation required for missions of interest
- Cannot operate megawatt class steady-state in current facilities
- Must be able to correlate MW class pulsed thruster operation and steady state data
- Data must enable rational extrapolation to high power levels

How do we realistically study MPD thruster performance and life using currently available facilities?

CD-91-54829



SPACE PROPULSION TECHNOLOGY DIVISION

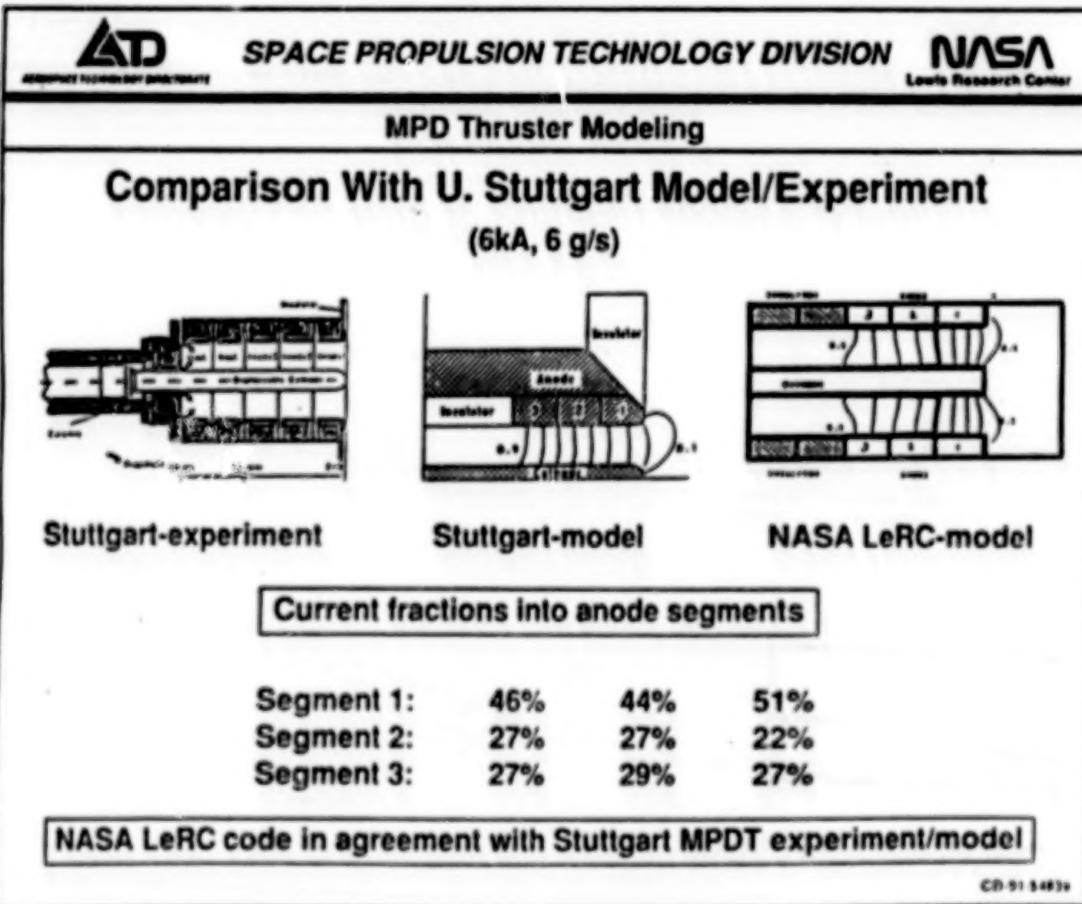
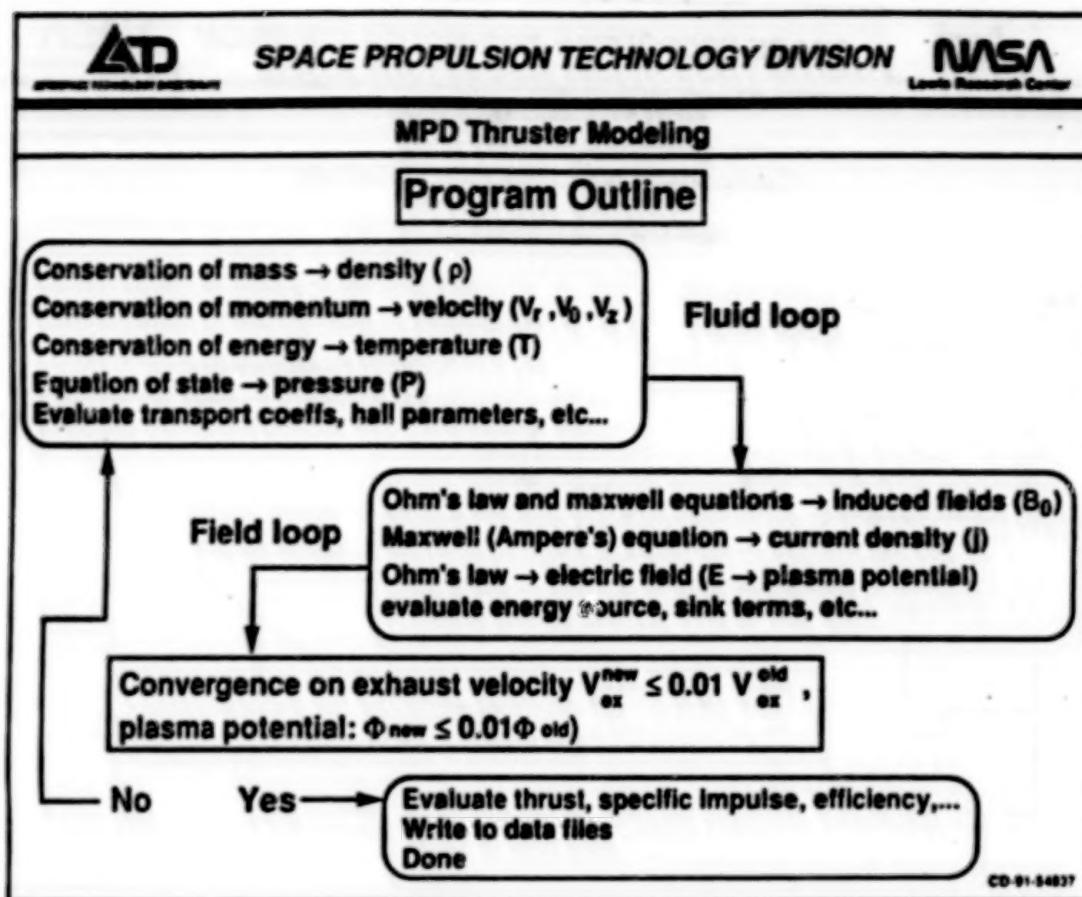


MPD Thruster Technology

Diagnostics

- X-Y probe positioning stand
 - Electrostatic probes
 - enclosed current contours
 - Axial applied B field distribution
- Plume imaging
 - Correlate ion density distribution with applied field
- Spectroscopy
 - Non-invasive temperature and density measurements

CD-91-54829

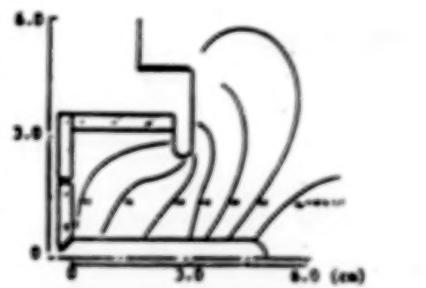
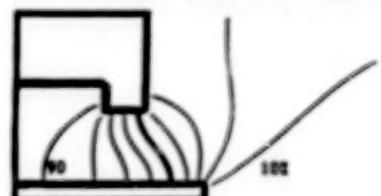




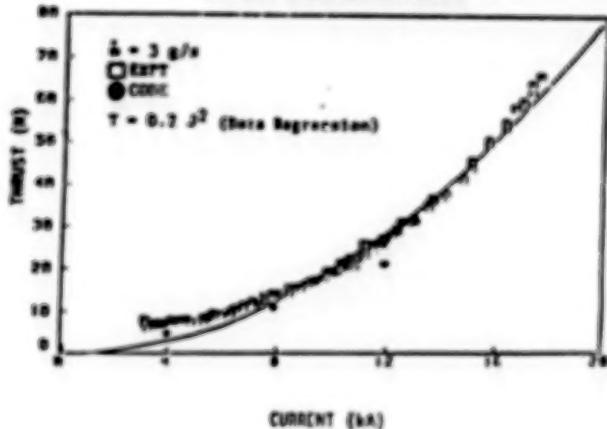
SPACE PROPULSION TECHNOLOGY DIVISION

NASA
Lewis Research Center

MPD Thruster Modeling

Comparison with Princeton University
Half-Scale Benchmark ThrusterENCLOSED CURRENT CONTURS (MEASURED)
12.4 kA, 1.3 g/s, QUASI-STEADY OPERATIONENCLOSED CURRENT CONTURS (PREDICTED)
12.4 kA, 1.3 g/s, STEADY-STATE OPERATION

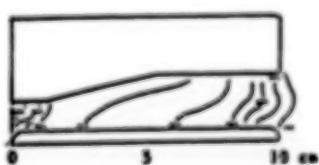
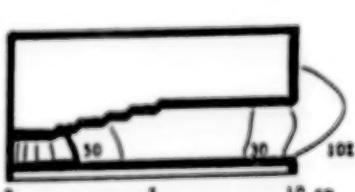
Thrust Characteristics



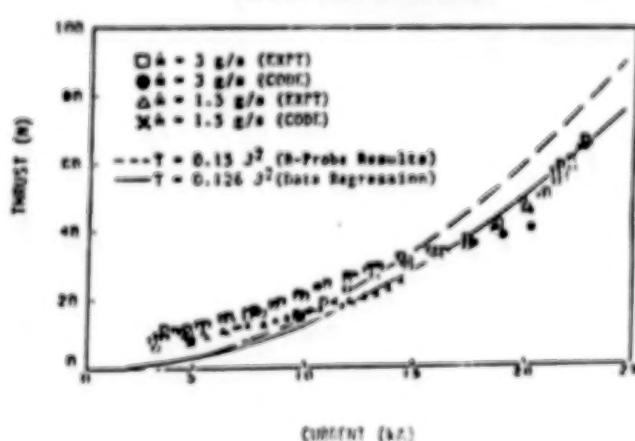
SPACE PROPULSION TECHNOLOGY DIVISION

NASA
Lewis Research Center

MPD Thruster Modeling

Comparison with Princeton University
Half-Scale Flared Anode ThrusterENCLOSED CURRENT CONTURS (MEASURED)
7.9 kA, 3 g/s, QUASI-STEADY OPERATIONENCLOSED CURRENT CONTURS (PREDICTED)
7.9 kA, 3 g/s, STEADY-STATE OPERATION

Thrust Characteristics





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NASA
Lang Research Center

MPD Thruster Modeling

Status

- Self-field version of MPDT code operational
 - Modest execution times 3-5 hours VAX-CPU)
 - General agreement with experimental results
 - Thruster performance evaluations underway
- Applied-field version of code under development
 - Routines for applied-B distributions incorporated
 - Preliminary testing/modification in progress

CD-81-54845



SPACE PROPULSION TECHNOLOGY DIVISION

NASA
Lang Research Center

KEY TECHNICAL ISSUES



KEY SCALING ISSUES

- TWO PRIMARY CONCERNS
 - POWER LEVEL SCALING
 - QUASI-STEADY VS. STEADY STATE
- ISSUES MUST BE ADDRESSED USING
 - THEORETICAL MODELS TO ESTABLISH TRENDS AND DEPENDENCIES
 - HGIH FIDELITY PERFORMANCE MEASUREMENTS
 - DETAILED DIAGNOSTICS OF PLASMA AND ELECTRODE PROCESSES USED TO:
 - A. ESTABLISH FUNDAMENTAL RELATIONSHIPS
 - B. VERIFY MODELS



PERFORMANCE EXPECTATIONS:

MUST EVALUATE EFFECTS OF :

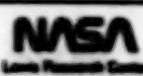
- PROPELLANT AND APPLIED FIELD
- ELECTRODE SIZE AND SHAPE
- PROPELLANT INJECTION

RELATION BETWEEN QUASI-STEADY AND STEADY-STATE:

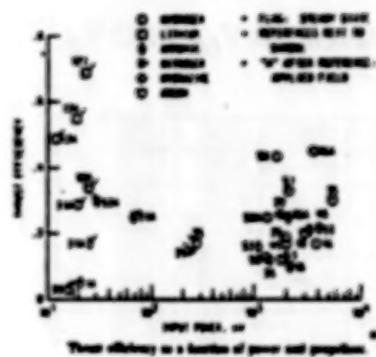
- MUST ESTABLISH DATA BASE WITH CORRECT PROPELLANT IN THE APPROPRIATE OPERATING RANGE (J^2/m^3)
- MUST MEASURE PERFORMANCE, CURRENT DISTRIBUTIONS, PLASMA AND ELECTRODE PARAMETERS



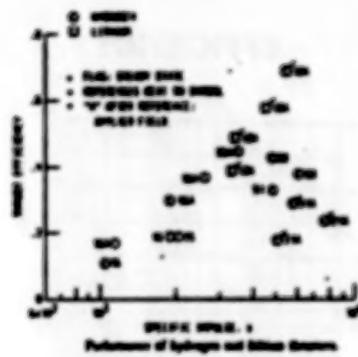
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PERFORMANCE EXPECTATIONS



Specific Thrust vs. Specific Power



Specific Thrust vs. Specific Power

- NOT CORRELATED WITH POWER
- STRONGLY INFLUENCED BY
 - PROPELLANT CHOICE
 - APPLIED OR SELF-FIELD

* Sovey, J. and Manteikis, M. "Performance and Lifetime Assessment of Magnetoplasmadynamic Arc Thruster Technology", J. Propulsion and Power, Vol.7, No. 1, Jan-Feb 1991

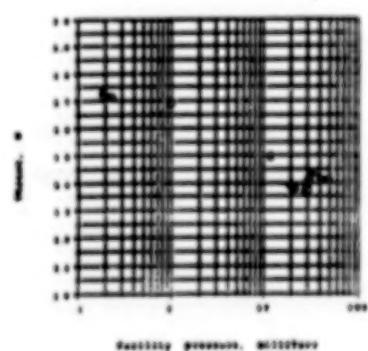


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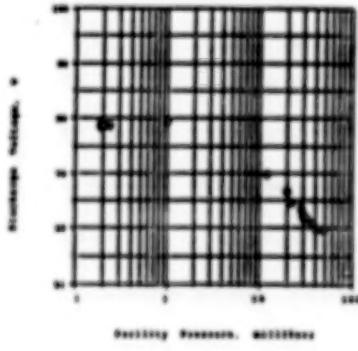
FACILITY REQUIREMENTS

THRUST



Facility Pressure, millibar

DISCHARGE VOLTAGE



Facility Pressure, millibar

4" D, 3" L ANODE, 0.1 G/S ARGON, 1500 A DISCHARGE, $B_z = .1$ T

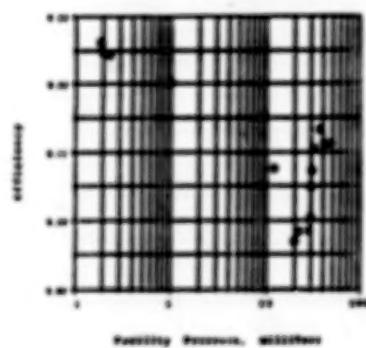


SPACE PROPULSION TECHNOLOGY DIVISION

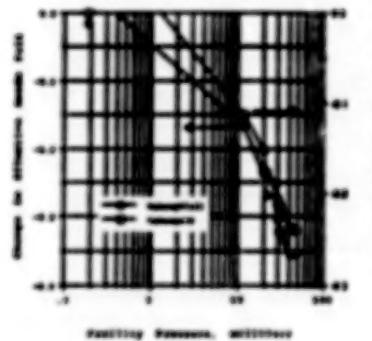


FACILITY REQUIREMENTS

EFFICIENCY



CHANGE IN V_{an} AND V_d



Similar anode heat xfer effect observed
by Saber with self-field thrusters

4" D, 3'L ANODE, 0.1 G/S ARGON, 1500 A DISCHARGE, $B_z = .1$ T



SPACE PROPULSION TECHNOLOGY DIVISION

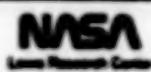


POTENTIAL MPDT FACILITIES

FY	FACILITY	THRUSTER POWER, MW		OPERATION TIME, HR	ESTIMATED COST, \$K
		H2	AR		
PRESENT	LERC T5,T6	0.1 (DEM)	0.22 (DEM)	CONT.	-----
1992	LERC T5	0.7-1	1	1-2	250 K
1993	LERC T5	1-1.5	2	4-6	400 K
1995	LERC T6	1-1.5	2	CONT.	3500-5000
1995	LLNL MFTF	1-5		CONT.	5000-7000
1998	LERC T6	1-5	1-5	CONT.	TBD



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MATERIAL LIMITATIONS

ANODE:

- MEASURED HEAT FLUX AT HIGH POWER $> 5 \text{ KW/CM}^2$
 - LITHIUM HEAT PIPES LIMITED TO $< 0.5 \text{ KW/CM}^2$
 - OPTIMIZED BEAM DUMP (Cu) LIMITED TO $\sim 5 \text{ KW/CM}^2$
 - SSME THROAT HEAT FLUX $\sim 16 \text{ KW/CM}^2$ (relevance?)

CATHODE:

- CURRENT DENSITIES AT HIGH POWER $> 100 \text{ A/CM}^2$
 - LONG LIFE CATHODES LIMITED TO CURRENT DENSITIES $\leq 20 \text{ A/CM}^2$ (LOW W.F. TWT CATHODES)

INSULATORS:

- KNOWN TO FAIL AFTER PROLONGED EXPOSURE TO UV AND HIGH TEMPERATURE

• WE MUST SELECT GEOMETRIES WHERE PERFORMANCE AND ENGINEERING LIMITS CAN BE EVALUATED

* PRINCETON UNIVERSITY



SPACE PROPULSION TECHNOLOGY DIVISION



FACILITY LIMITATIONS:

- MUST MEASURE PERFORMANCE AT PRESSURES $< 5 \times 10^{-4} \text{ T}$
- FACILITY PRESSURE HAS LARGE EFFECT ON ANODE HEAT XFER, NOT CLEAR ON CATHODE

THRUSTER VIABILITY:

- SHOULD FOCUS ON DEVICES WHICH MATCH ENGINEERING LIMITS FOR:
 - ANODE HEAT TRANSFER
 - CATHODE CURRENT DENSITY
 - INSULATOR LIMITS

55-20

N 92-10049~~0051~~

Appendix H

p. 20

L4405312

LOS ALAMOS NEP RESEARCH IN ADVANCED PLASMA THRUSTERS

Kurt Schoenberg and Richard Gerwin

Presented to the NASA
MPD Thruster Technology Workshop
May 16, 1991

PLASMA THRUSTER RESEARCH

Los Alamos has initiated research in advanced plasma thrusters that capitalizes on Laboratory capabilities in plasma science and technology

THE PROGRAM GOAL:

- Elucidate the scaling issues of MPD thruster performance in support of NASA's MPD thruster development program

THE PROGRAM OBJECTIVE:

- Address multi-megawatt, large scale, quasi-steady-state MPD thruster performance

2001-98

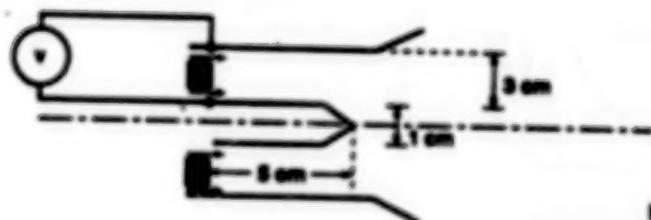
ADVANCED PLASMA THRUSTERS

Active Research Activities

- A CTX coaxial plasma gun, with tungsten-coated electrodes, is being operated as a function of current, gas pressure, gas type, applied axial magnetic field, and electrode polarity.
- The steady-state properties of nozzle-based coaxial plasma guns are being modeled by an evolving magnetic Bernoulli equation that provides analytic predictions for thruster power, mass flow rate, thrust, and specific impulse.
- Research Results:
 - A new quasi-steady-state operating regime has been obtained at SEI-relevant power levels (5 to 10 MW), that enables direct coaxial gun - MPD comparisons of thruster physics and performance.
 - Radiative losses are negligible
 - Operation with an applied axial magnetic field shows the same operational stability and exhaust plume uniformity benefits seen in MPD thrusters.
 - Observed gun impedance is in close agreement with the magnetic Bernoulli model predictions.
 - Spatial and temporal measurements of magnetic field, electric field, plasma density, electron temperature, and ion/neutral energy distribution are underway.
 - Model applications to advanced mission logistics are underway.

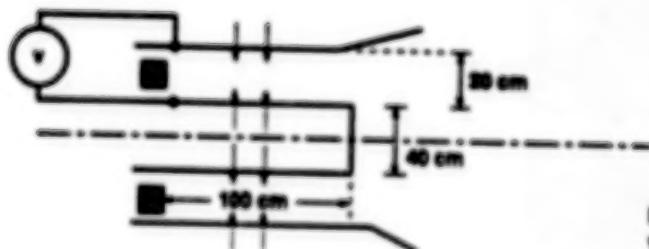
ELECTROMAGNETIC THRUSTERS: J, B, DRIVES ρv_z

MPO THRUSTERS



$I = 50$ kA
 $V = 100$ volts
 $n = 10^{19} - 10^{21} \text{ m}^{-3}$

COAXIAL GUNS



$I = 50-100$ kA
 $V = \text{few 100 volts - few kV}$
 $n = 10^{19} - 10^{21} \text{ m}^{-3}$

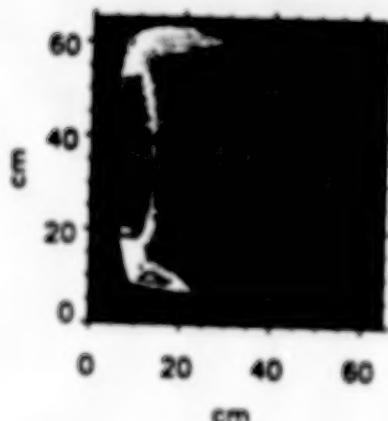
COAXIAL GUN DISCHARGE # CTX19645



Diagram

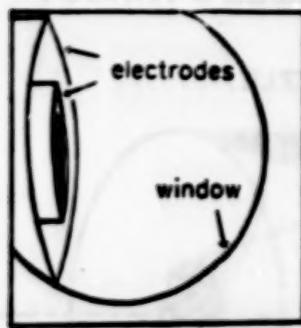


Visible Emission



Intensity Contours (0-255)

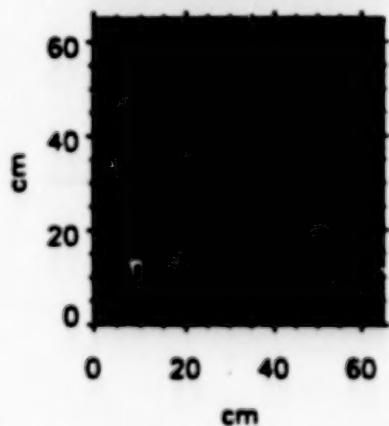
COAXIAL GUN DISCHARGE # CTX19659



Diagram



Visible Emission

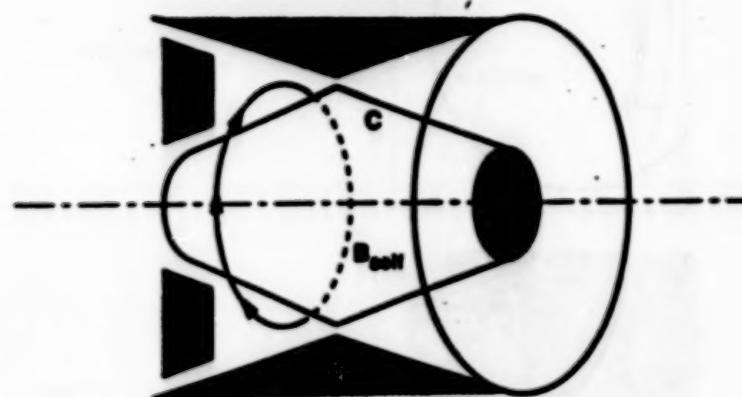


Intensity Contours (0-255)

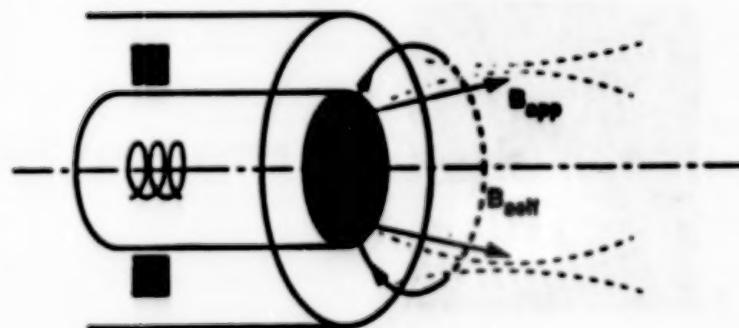
ORIGINAL PAGE IS
OF POOR QUALITY

DEFLAGRATION + NOZZLE = THRUST

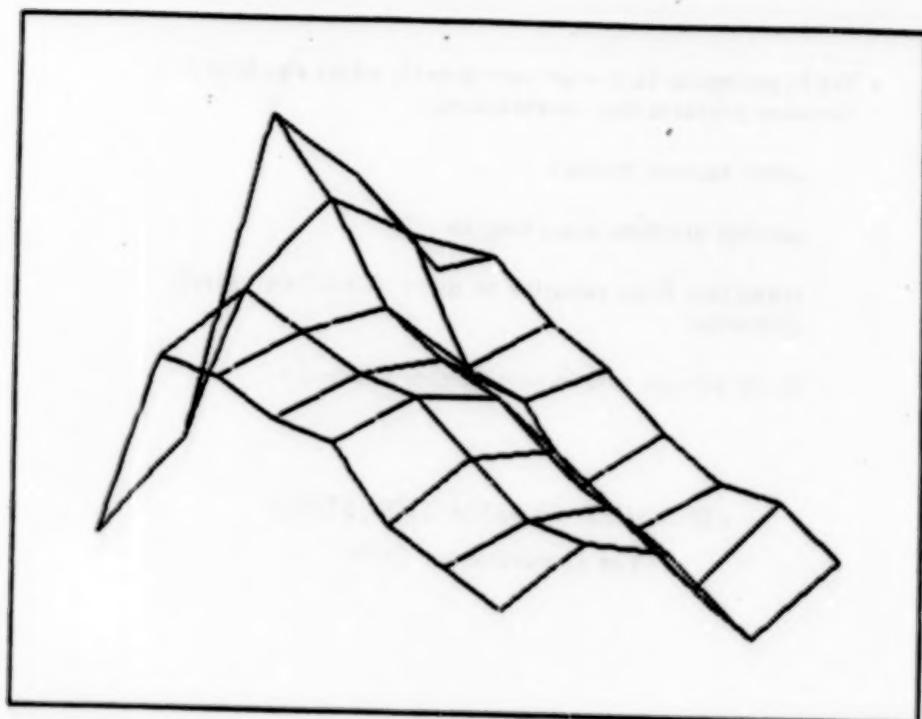
BUILT-IN NOZZLE



MAGNETICALLY-FORMED NOZZLE



PLASMA THRUSTER RESEARCH
Spatial Field Measurements



3-D Spatial | B | plot

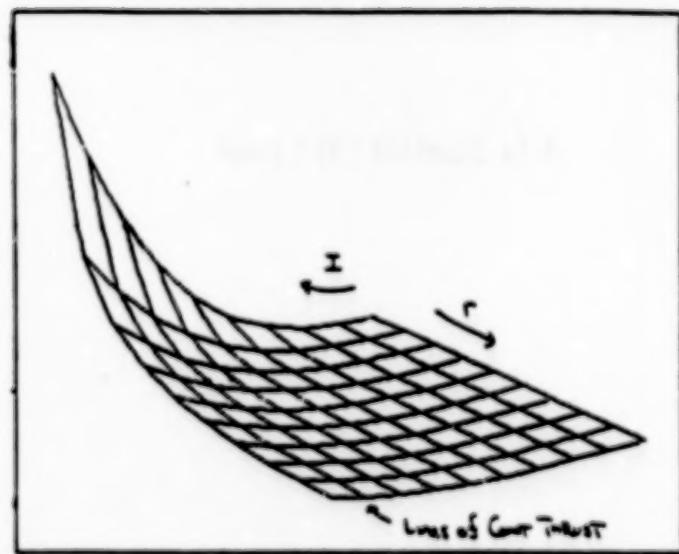
ADVANCED PLASMA THRUSTERS

The Importance of Scale

- We hypothesize that scale is important to optimize MMW mission applications
- We hypothesize that scale may directly affect the MMW thruster performance characteristics
 - lower current density
 - smaller gradient scale lengths
 - transition from resistive to more "ideal like" MHD operation
 - lower plasma turbulence - higher efficiency

ADVANCED PLASMA THRUSTERS

The Importance of Scale



Thrust power as a function of I and r

ADVANCED PLASMA THRUSTERS

Envisioned Experimental Program

NEAR-TERM

- Characterize QSS power balance at large scale, MMW
 - Electrode Losses
 - Radiation
 - Axial, radial transport
- Compare global loss estimates with locally determined power balance

FARTHER-TERM

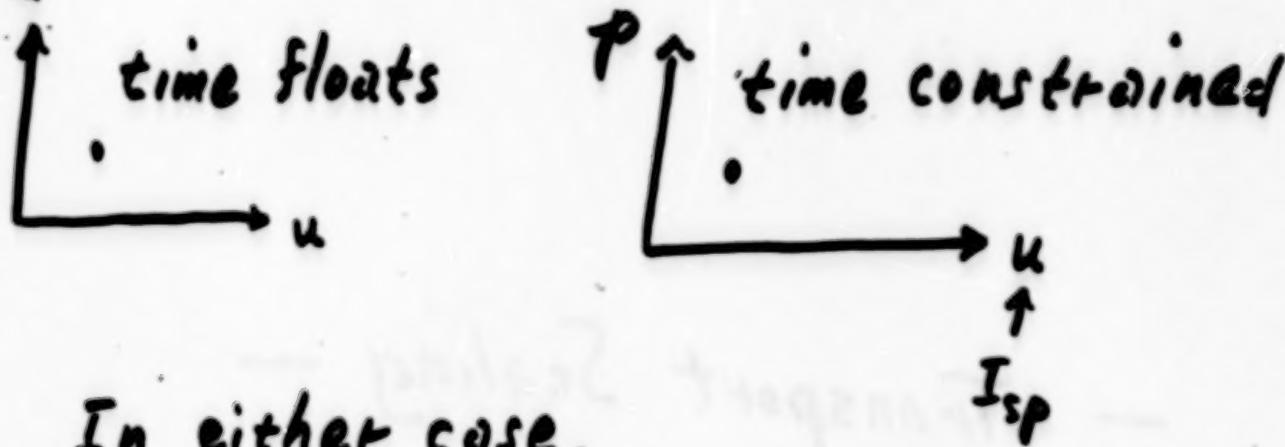
- Achieve QSS and mass-flow steady state
- Benchmark power balance
- Address performance optimization
 - electrode configuration
 - nozzle configuration (magnetic)
 - spatial scale

SCALING ISSUES FOR MPD THRUSTERS

- Possible Reasons for Scaling with R -
- Mission Scaling
- Transport Scaling
- Macroscopic Stability
- Microscopic Stability
- Optimization of Thruster Efficiency

SCALING ISSUES FOR MPD THRUSTERS

- Mission Scaling -



— M_{EH} , M_{PT} , M_{GP} all scale with m_{PT} —

where $m_{PT} \equiv \frac{1}{2} N_{th} \rho_0 A_0 f$ ($f \equiv V_0/V_e$) .

Note: $m_{PT} \sim N_{th} \rho R^2$ (fixed $\frac{A_0}{R}$)

— $I \sim R \rho^{\frac{1}{2}}$ for fixed I_{sp} . —

m_{PT} : "specific mass of the propellant"

SCALING ISSUES FOR MPD THRUSTERS

— Transport Scaling —

May be related to the mechanism of plasma production and "ingestion".

Scaling Issues for MPD Thrusters

- Plasma Production and Heating -

Model: "Sand dropped on Conveyor Belt"

Assume $T_e = T_i$:

Approach: Boltzmann Equation with Source

Get: $\left(\frac{d}{dt} = \frac{\partial}{\partial t} + \vec{V} \cdot \nabla \right)$

$$\frac{2}{\gamma-1} \frac{d \vec{T}}{dt} + 2 \vec{T} \nabla \vec{V} =$$

= Ohmic Heating + Viscous Heating

- Thermal Conduction Loss

$$+ n_0 \langle \sigma v \rangle_0 \left[\frac{1}{2} m_i V^2 - \frac{2}{\gamma-1} T - e_i \right] \quad \} \text{CV!}$$

$$\rightarrow + n_* \langle \sigma v \rangle_* \left[\frac{1}{2} m_i V^2 - \frac{2}{\gamma-1} T - (e_i - e_*) - \frac{n_0 \langle \sigma v \rangle_0^*}{n_* \langle \sigma v \rangle_*} e_* \right]$$

ionization
of excited states:

where $\frac{1}{2} m_i V^2$ means $\frac{1}{2} m_i (V - V_m)^2$.

SCALING ISSUES FOR MPD THRUSTERS

- Transport Scaling -

- Mass Transport ($\omega_{ce} < \nu_e$)

$$\frac{t_2}{t_1} \sim R_{mag} \sim \left(\frac{V_z \Delta}{D_2} \right) \sim T^2 R \sim \left(\frac{I}{RP^{1/2}} \right)^* R$$

- Mass Transport ($\omega_{ce} > \nu_e$)

$$\frac{V_r t_2}{\Delta} \sim \frac{c/\omega_{pi}}{R} \quad \begin{bmatrix} \text{Ions carry} \\ \text{some current.} \end{bmatrix}$$

- Heat Transport by classical/ ions

8. $\left[\frac{MW}{m^2} \right] \quad (\text{next slides})$

SCALING ISSUES FOR MPD THRUSTERS

PREDICTIONS FROM "CONVEYOR BELT" MODEL OF ION HEATING (HYDROGEN)

$$\left(\frac{1}{2} m_i V^2 \right) \gg \Delta E \text{ (atomic)}$$

$$T_i(eV) = 5.0 \times 10^{10} \left(\frac{I^2}{nr^3} \right)_{MKS}$$

$$\frac{\omega_{ci}}{\nu_{ii}} = 4.6 \times 10^{29} \left(\frac{I^4}{n^{5/2} r^4} \right)_{MKS}$$

$$\frac{\omega_{ce}}{\nu_e} = 30 \frac{\omega_{ci}}{\nu_{ii}} \quad \text{assuming } T_e = T_i$$

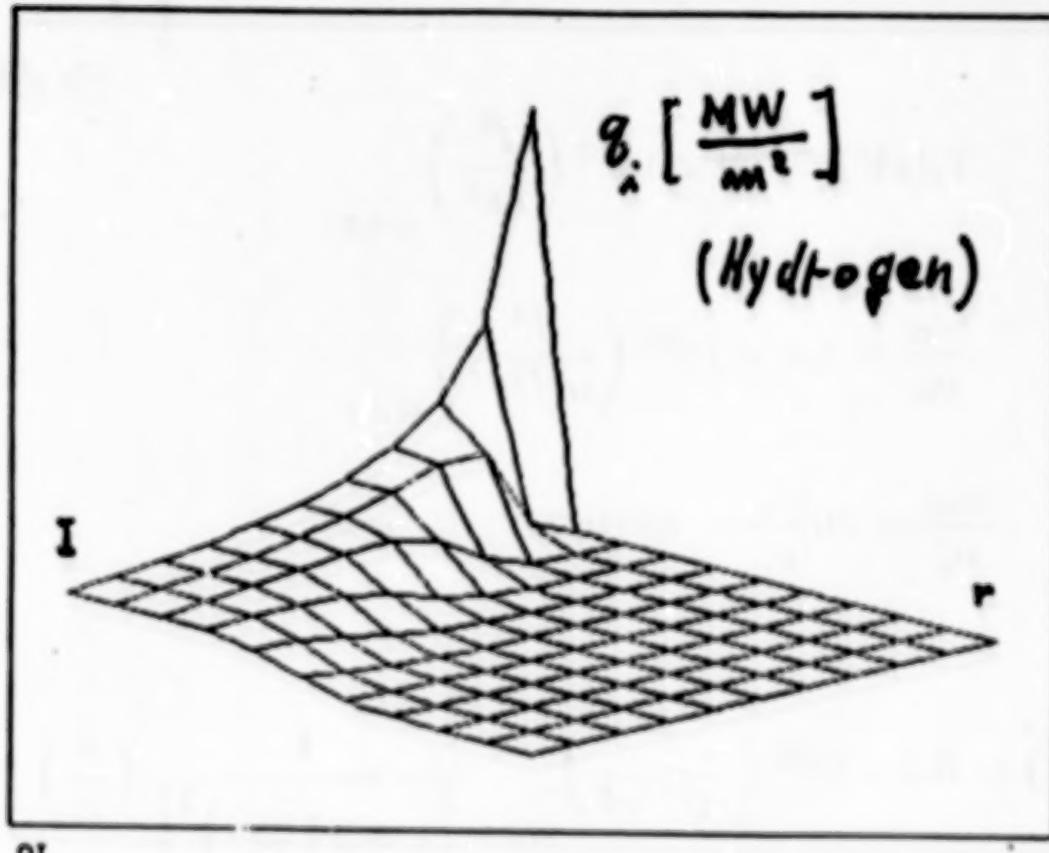
$$q_i (MW/m^2) = 6.3 \times 10^{33} \left(\frac{I^7}{n^{7/2} r^8} \right)_{MKS} \frac{1}{\left[1 + 2 \left(\frac{\omega_{ci}}{\nu_{ii}} \right)^2 \right]} \left(\frac{r}{\Delta} \right)$$

$$R_v = 0.58 \times 400 \times 10^{-40} \left(\frac{n^3 r^5}{I^4} \right)_{MKS} \left(\frac{\Delta}{r} \right) \left[1 + 3 \left(\frac{\omega_{ci}}{\nu_{ii}} \right)^2 \right]$$

SCALING ISSUES FOR MPD THRUSTERS

$$QI_{1,1} := QI[I_1, n_1, r_1] \quad I_0 = 5 \cdot 10^3 \quad r_0 = 0.01 \quad n_2 = 3 \cdot 10^{20}$$

$$I_{10} = 5.5 \cdot 10^4 \quad r_{10} = 0.51$$



QI

$$QI_{0,0} = 15.448$$

$$QI_{0,10} = 2.3 \cdot 10^{-10}$$

$$QI_{10,0} = 1.406$$

$$QI_{10,10} = 0.004$$

SCALING ISSUES FOR MPD THRUSTERS

- Macroscopic Stability -

The viscous Reynolds number
(with magnetized ions)
may become large
and may thereby induce
turbulent channel flow.

Scaling Issues for MPD Thrusters

— Turbulent Convection — ($\omega_{ci} > v_i$ case)

Viscous Reynolds number: $\frac{V \Delta}{D_v} = R_v$

Ion Shear Viscosity: $\frac{1}{7} \frac{v_{thi}^2}{v_i} \frac{v_i^2}{\omega_{ci}^2} = D_v$

$$v_i = \text{const.} \times m^{-3/2} T$$

Hence $R_v = \text{const.} \times \Delta \times \left(V \frac{B^2}{m} \frac{1}{T_i} \right)$

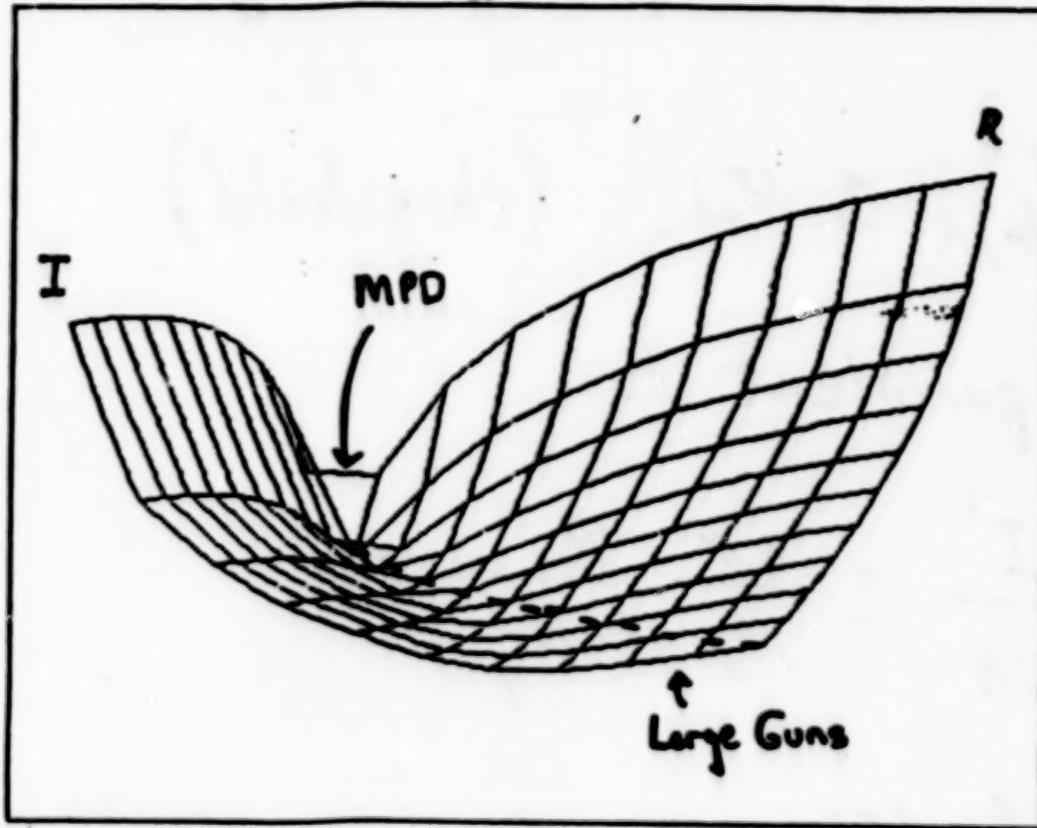
If T_i "does scale" (like V^2)

then $R_v = \text{const.} \times \Delta \times V^4 \sim \left(\frac{I^2}{M} \right)^4$

Scaling Issues for MPD Thrusters

$$RV1_{i,j} := \log [Rv[I_i, n_i, r_j]] \quad I_0 = 5 \cdot 10^3 \quad r_0 = 0.01 \quad n_1 = 2 \cdot 10^{20}$$

$$I_{10} = 5.5 \cdot 10^4 \quad r_{10} = 0.51$$



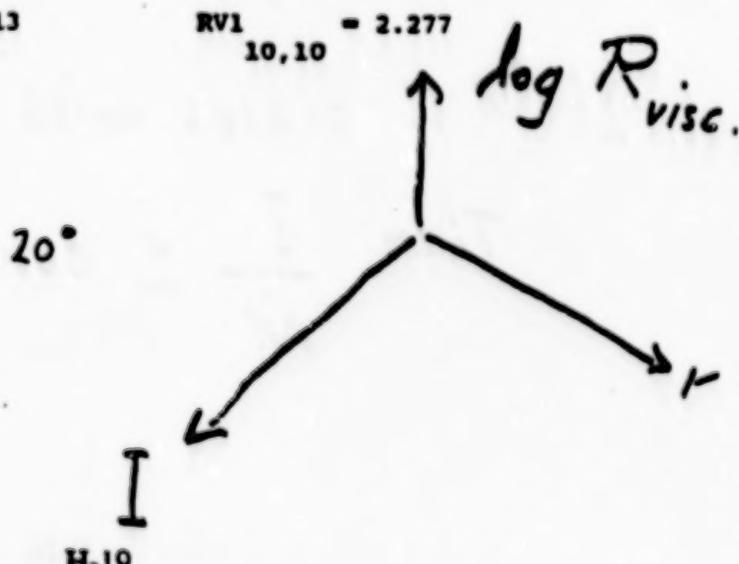
RV1

$$RV1_{0,0} = 2.964$$

$$RV1_{0,10} = 6.107$$

$$RV1_{10,0} = 7.13$$

$$RV1_{10,10} = 2.277$$



H-19

SCALING ISSUES FOR MPD THRUSTERS

— Microscopic Stability —

$$V_{dr,R} \lesssim v_{thi} \text{ (threshold)}$$

equivalent to

$$\frac{I^2}{\dot{M}} \lesssim \frac{4\pi}{\mu_0} \frac{R}{(c/\omega_{pi})} v_{thi}$$

If (T_i does not scale with V^2)

Then $\frac{I^2}{\dot{M}} \lesssim \text{approx. const.}$

If (T_i scales with $V^2 [\text{hi } I]$)

Then $\frac{I}{\dot{M}} \lesssim \text{const.} \leftarrow \begin{bmatrix} \text{observed} \\ \text{at hi } I \end{bmatrix}$

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Appendix I

MPD WORK AT MIT

by

M. Martinez-Sánchez

D.E. Hastings

PRESENTED AT THE MPD TURUSTER TECHNOLOGY WORKSHOP

NASA HEADQUARTERS, MAY 16, 1991

GOALS VS. ACHIEVEMENTS

	EFFICIENCY (%)	t_{sp} (sec.)	CATHODE EROSION ($\mu\text{g}/\text{C}$)
GOALS	50%	5000	10^{-4}
SELF FIELD MPD	42% (H ₂ , Ref. 1) 30% (A, Ref. 2)	6000 (H ₂ , Ref. 1) 3000 (A, Ref. 2)	2×10^{-3} (H ₂ , Ref. 9) 6×10^{-4} (N ₂ , Ref. 9) 1.3×10^{-3} (A, Ref. 9)
APPLIED FIELD MPD	70% (Li, Ref. 3) 70% (H ₂ , Ref. 4) 50% (NH ₃ , Ref. 4)	6000 (H ₂ , Ref. 5) 5000 (Li, Ref. 3) 2000 (A, Ref. 6)	3×10^{-5} (H ₂ , Ref. 7) 2×10^{-3} (NH ₃ , Ref. 8)

1. Uematsu, K. et al. 1984 5. Arakawa Y. et al. 1987 9. Auweter-Kurtz, M., et al. 1990
2. Wolff, M. et al. 1984 6. Connolly et al. 1971 10. Burch, J. et al. 1988
3. Connolly, D.J. et al 1968 7. Ducas, A.C. et al. 1964
4. Tahara, H. et al. 1988 8. Eshker, D.W., 1969

ROADBLOCKS

PERFORMANCE FEATURE	LIMITING EFFECT	COMMENTS
THRUST EFFICIENCY	FROZEN LOSSES ELECTRODE DROPS	<ul style="list-style-type: none"> HIGHEST AT "ONSET" LIMITING IONIZATION/KINETIC ENERGY, (MAY DEPEND-GEOMETRY) FORCE SELF-FIELD MPD TO MW POWER LESS IMPORTANT WITH APPLIED FIELD
SPECIFIC IMPULSE	VARIOUS FORMS OF "ONSET"	<ul style="list-style-type: none"> HIGHEST WITH LIGHTEST GASES
LIFE (EROSION)	ELECTRODE EVAPORATION GAS IMPURITIES CATHODE MICROARCS MASSIVE ARCS AT ONSET	<ul style="list-style-type: none"> Thermal design, impregnant dispenser composition control May be irrelevant for hot operation Ultimate limiter

THE MIT PROGRAM

- SUPPORTED BY AFOSR GRANTS (1983 - PRESENT)
- MAINLY THEORETICAL WORK, WITH TWO EXCEPTIONS:
 - JOINT PROGRAM WITH R & D ASSOCIATES (HEIMERDINGER, KILFOYLE)
 - JOINT PROGRAM WITH PHILLIPS LAB (GAIDOS)
- HAS CONCENTRATED ON MODELING FLUID DYNAMICS AND PHYSICS OF SELF-FIELD THRUSTERS:

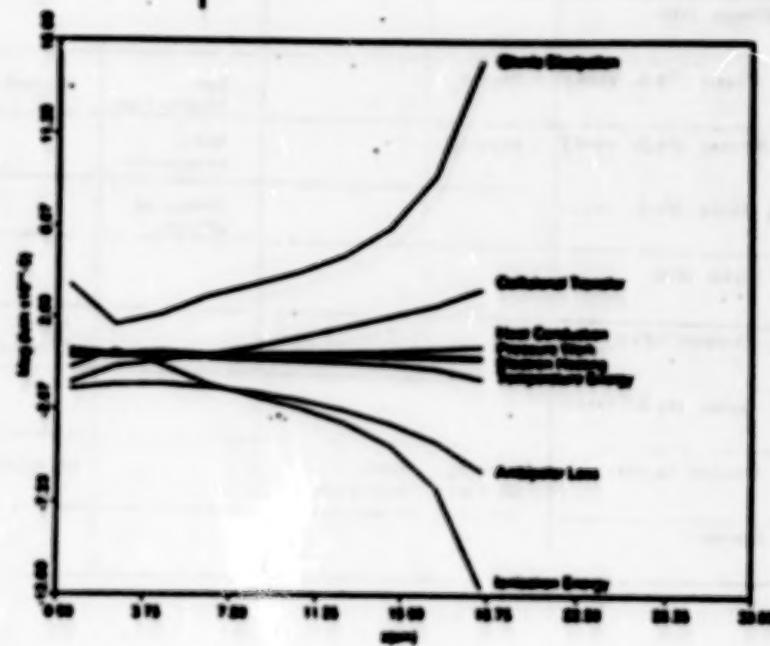
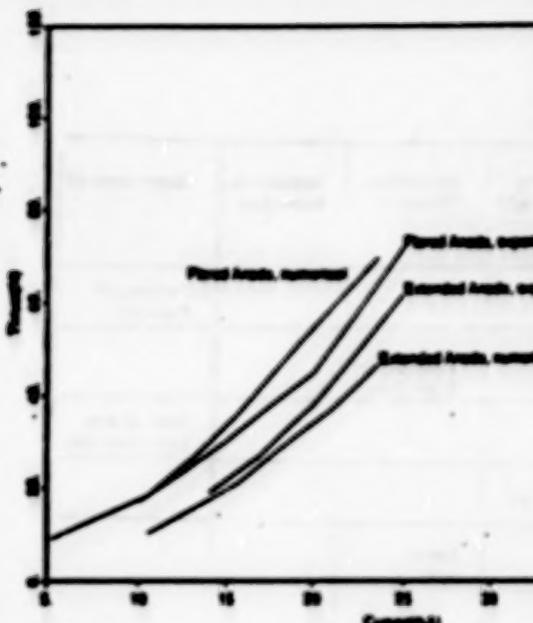
<u>1-D MODELS</u>	DYNAMICS OF HIGH MAGNETIC REYNOLDS NO. FLOWS EFFECTS OF AREA CONTOURING EFFECTS OF KINETICS, TRANSPORT
<u>2-D MODELS</u>	ANODE DEPLETION AND OTHER HALL EFFECT CONSEQUENCES FRICTION, DIFFUSION, HEAT LOSS DEVELOPMENT OF MACROSCOPIC INSTABILITIES
<u>STABILITY</u>	IONIZATION, LOWER HYBRID AND ELECTROTHERMAL INSTABILITIES
<u>KINETICS</u>	UPPER LEVEL POPULATIONS, INLET EFFECTS

THREE-DIMENSIONAL MODELING

	1-D Models	1 1/2-D Models	2-D Models (Numerical)	2-D Models (Analytical)	Stability Theory	Radiation, kinetics	Experimental
D. Heimeldinger (Ph.D.)	Contouring	Anode Depletion					Concurred Channel
Tao Wing Rose (MS)					Ionization Stability		
D. Ellingson (MS)							Orbit plane Spectroscopy
J.M. Chanty (Ph.D. cond.)	High E_{th}		Low Interactions	Asymptotics			
EH Niewood (Ph.D. cond.)	Physics		Ball, inaccurate		Lower Hybrid		
Scott Miller (Ph.D. cond.)			Transport effects				
Jeff Proble (MS)					Electro-thermal		
Eric Shappard (Ph.D. cond.)				Inlet Effects		Radiation, Kinetics	
Eric Goldin (Ph.D. cond.)							Sheet Physics
M. Martinez-Sanchez	High E_{th} Contouring	Anode Depletion		Asymptotics	Electro-thermal		
D. Hastings					Lower Hybrid		

QUASI ONE DIMENSIONAL MODELING

- BY SACRIFICING GEOMETRICAL DETAIL, EXPLORATION OF A BROAD RANGE OF PHYSICAL EFFECTS IS POSSIBLE IN THE CONTEXT OF 1-D MODELS WITH AREA VARIATION
- SHOWN ARE EXAMPLES OF E. NIEWOOD'S RESULTS ILLUSTRATING
 - DEGREE OF AGREEMENT WITH THRUST DATA FROM TWO PRINCETON U. THRUSTERS
 - RELATIVE IMPORTANCE OF VARIOUS ELECTRON ENERGY SOURCES/SINKS ALONG THE LENGTH OF A THRUSTER



TWO-DIMENSIONAL MODELLING - TRANSPORT EFFECTS

- VISCOSITY DRAG IMPORTANT IN SLENDER THRUSTERS
- VISCOSITY DISSIPATION CONTRIBUTES TO HIGH ION TEMPERATURE
- DIFFUSION AND HEAT CONDUCTION IMPORTANT AS DAMPING EFFECTS
 - .. RESULTS BELOW FROM S. MILLER'S WORK, FOR D. HEIMERDINGER'S CHANNEL, NEGLECTING HALL EFFECT.
 - .. NOTICE BOUNDARY LAYER DEVELOPMENT TO NEAR-FULLY DEVELOPED FLOW.
 - .. LACK OF SYMMETRY IS REAL, AND ARISES FROM ENERGY TRANSPORT BY TRANSVERSE CURRENT.

Two-Dimensional Viscous MPD Flow

Magnetic Field



Max = 0.1T
Min = 0.0T
Inc = 0.004T

Fluid Velocity



Max = 5000m/s
Min = 0 m/s
Inc = 200m/s

Gas Temperature



Max = 10000K
Min = 0K
Inc = 400K

TWO-DIMENSIONAL MODELING - HALL EFFECT

- THE HALL EFFECT STRONGLY DISTORTS THE PLASMA FLOWS, AS SHOWN IN THE 2-D RESULTS SHOWN NEXT. CONDITIONS ARE
 $H = 2 \text{ CM}$ $L = 10 \text{ CM}$ $B_0 = 0.1 \text{ T}$ ($I = 30 \text{ kA}$)
ARGON, $m = 4 \text{ g/sec}$
- NOTICE STRONG AXIAL CURRENT ALONG ANODE. THIS PRODUCES LARGE DISSIPATION (SEE T_e MAP) AND HIGH IONIZATION FRACTION. PLASMA IS KEPT ELECTROTHERMALLY STABLE BY ELECTRON HEAT CONDUCTION
- VERY STEEP VOLTAGE DROP NEAR ANODE FROM LOCALLY HIGH HALL FIELD. SEE POTENTIAL CUT IN NEXT GRAPH. THIS WAS SEEN IN OUR TESTS UNDER SIMILAR CONDITIONS (SEE BELOW)

Two Dimensional MPD with Hall Effect

Current Lines



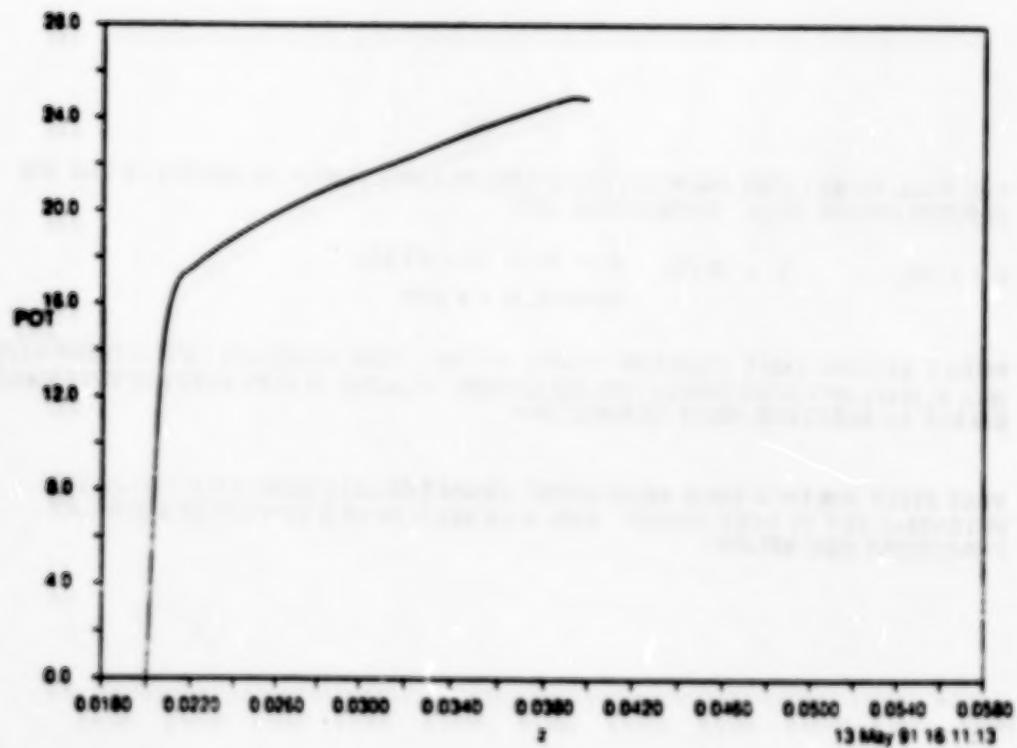
Electron Temperature



Ionization Fraction

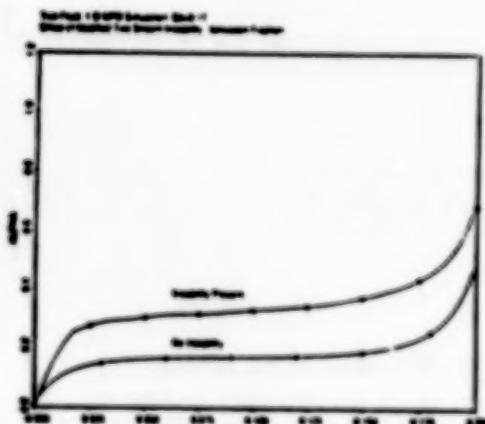


2-D MPD EQUATIONS
POT



Microscopic Instabilities in MPD Flows

- Microscopic plasma instabilities have been shown to be common in many plasma regimes, eg. fusion plasmas, ionospheric plasmas.
- In MPD thrusters, current represents a large source of free energy, which may drive instabilities.
- Modified Two Stream instability was chosen as a likely candidate for importance in MPD.

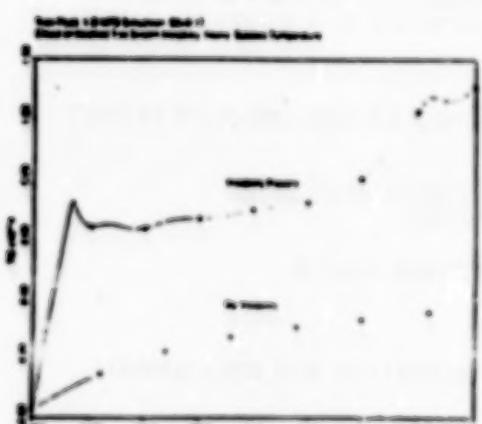


Modified Two Stream Instability

Significant increases in heavy species temperature due to anomalous heating

Significant increase in ionization fraction due to increased dissipation

Increase in plasma resistivity but no macroscopic plasma instability

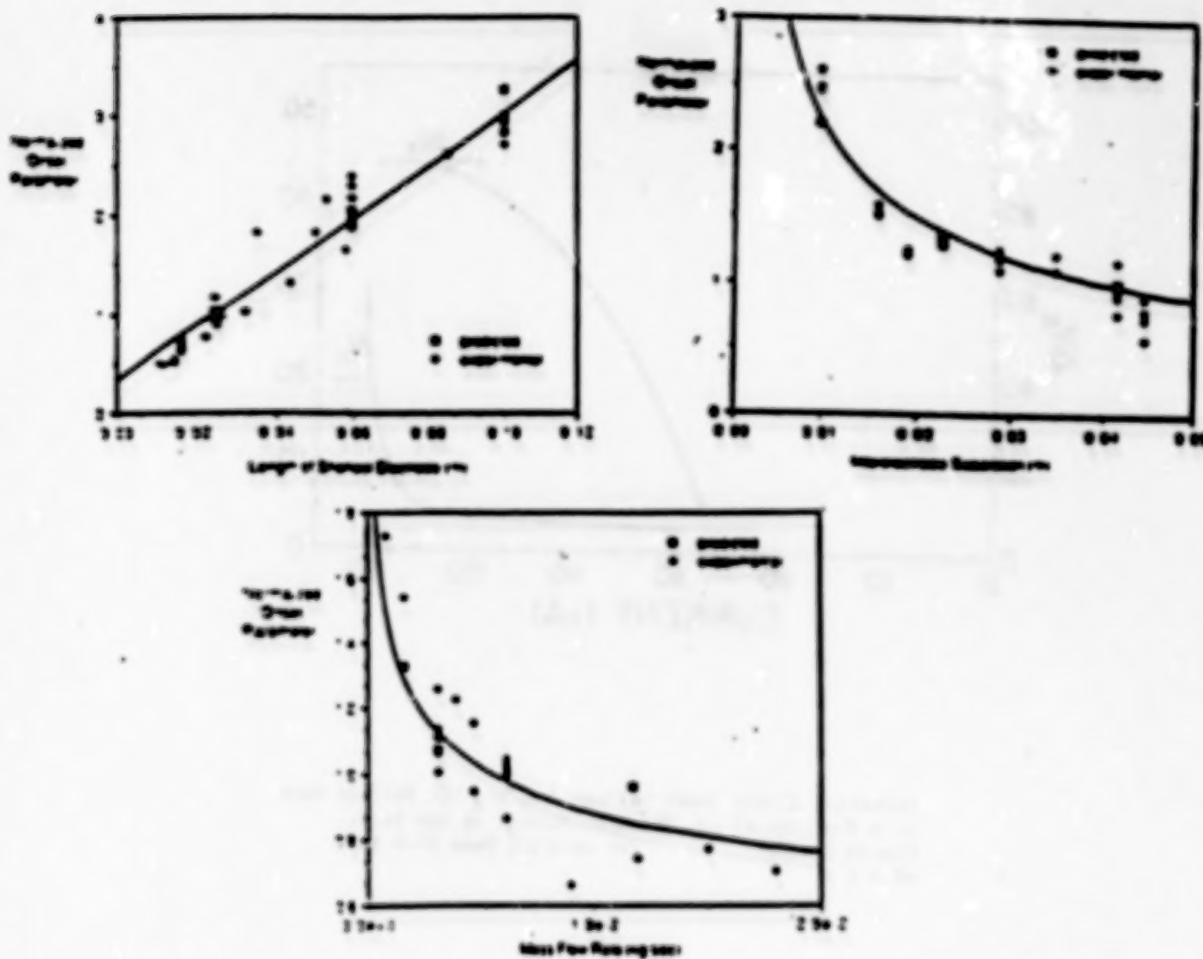


Conclusions

- Plasma can evolve to new equilibrium in presence of Modified Two Stream Instability, with increased ionization fraction and heavy species temperature.
- Microscopic plasma instabilities could lead to large variations in operating voltage and, therefore, efficiency.
- Plasma instabilities are important in modelling MPD flows.
- Experiments, both existing and, when required, new, should be used to ascertain what types of instabilities may be excited in MPD flows.

ELECTROTHERMAL STABILITY THEORY

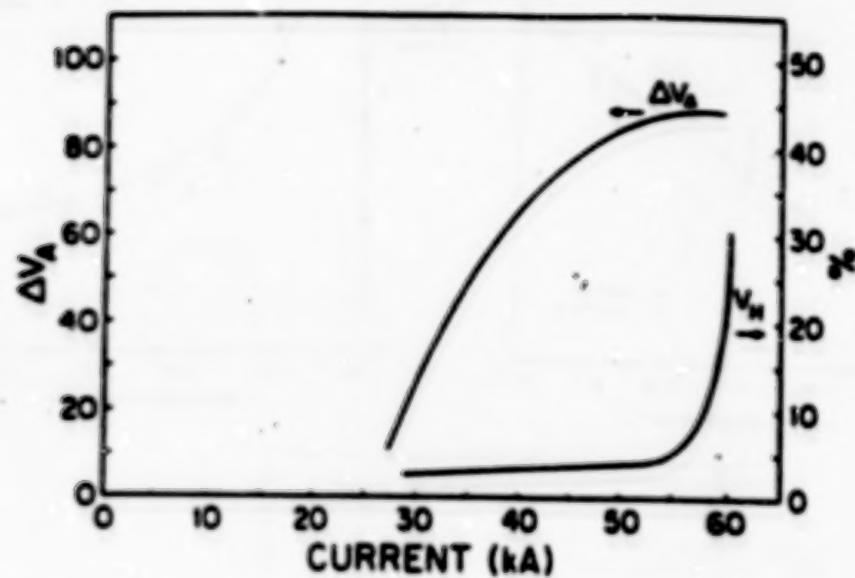
- UNBOUNDED PLASMA BECOMES STATICALLY UNSTABLE NEAR FULL IONIZATION. CONDUCTIVITY $\propto T_e^{3/2}$, SO REGIONS OF HIGHER T_e TEND TO CHANNEL CURRENT, FURTHER RAISING T_e .
- EFFECT IS MASKED AT PARTIAL IONIZATION BY ENERGY ABSORPTION IN IONIZATION PROCESS. SIMILARLY, HEAT DIFFUSION OR ELECTRON-ION PAIR DIFFUSION DAMPEN IT FOR SMALL (LESS THAN $\sim 2 - 4$ CM) LENGTHS
- WE COUPLED A STANDARD STABILITY ANALYSIS WITH A 1-D MPD MODEL TO PREDICT CONDITIONS WHEN
 - INSTABILITY WOULD DEVELOP SOMEWHERE (USUALLY AT EXIT)
 - GROWTH RATE WOULD EXCEED SOME THRESHOLD
- RESULTS SHOW GOOD AGREEMENT WITH ONSET TRENDS VERSUS
 - LENGTH
 - WIDTH
 - MASS FLOW RATE (THIS DEVIATION FROM $1^2/m$ SCALING WAS UNEXPLAINED BEFORE)



SEPARATION OF 'ONSET' AND ANODE DEPLETION

- FROM OUR COOPERATIVE WORK WITH R&D ASSOCIATES (HEIMERDINGER, 1988)
- USING QUASI - 2D CHANNEL AND 4g/sec. ARGON
- PROBE AT ~ 3 mm FROM ANODE DETECTS LARGE AV, AT ~ 30 KA (CLOSE TO THEORY PREDICTION), BUT PLASMA REMAINS "QUIET"
- AT 60 KA, LARGE, QUASI-PERIODIC VOLTAGE FLUCTUATIONS OCCUR
 - VERY CLEAR SEPARATION OF EFFECTS

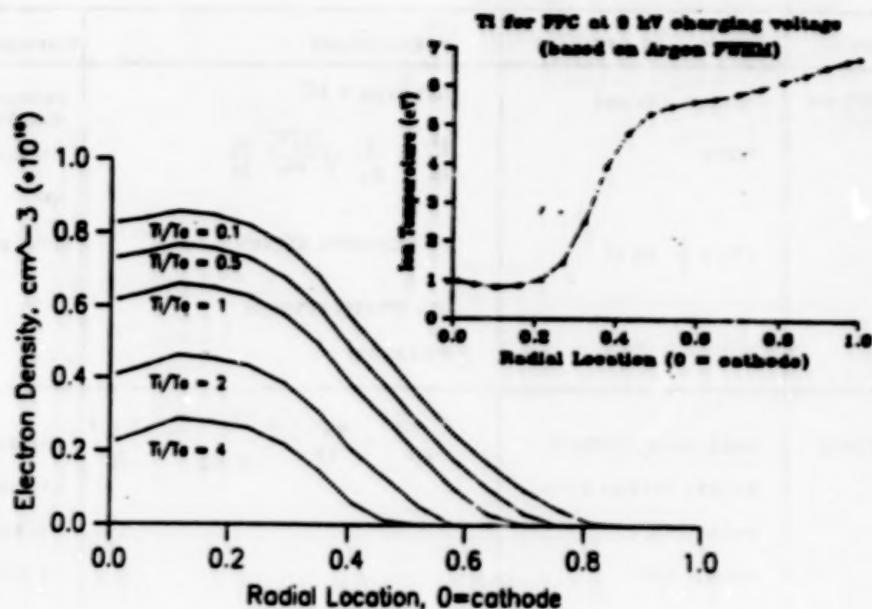
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OF POOR QUALITY



Variation of the Anode Voltage Drop and the Voltage Drop
as a Function of the Thruster Current in the Fully
Flared Channel for an Argon Mass Flow Rate
of 4 g/s

EXIT PLANE SPECTROSCOPIC MEASUREMENTS

- DURING THE SAME TEST SERIES, D. KILFOYLE USED A 1.36 m. SPECTROSCOPE TO MEASURE LINE WIDTHS AND LINE INTENSITY RATIOS OF ARGON II AND II LINES (II, USED AS A DIAGNOSTIC ADDITIVE)
- DATA SHOW HIGH ARGON ION TEMPERATURES (HIGHER THAN T_e IN THE ANODE REGION), WHICH COULD IMPLY THE PRESENCE OF MICRO-INSTABILITIES
- DATA ALSO SHOW STRONG ANODE DEPLETION (AT $I = 60$ kA), IN AGREEMENT WITH ΔV_a DATA



Radial profile of electron density in fully flared channel for various assumed values of T_e/T_i .

ONSET AS PERFORMANCE LIMITER PHENOMENA

- AT HIGH CURRENT/LOW MASS FLOW SEVERAL PHENOMENA OCCUR (NOT ALWAYS SIMULTANEOUSLY WHICH LIMIT I_c , I_p RANGE)

PHENOMENON	COMMENT
(a) SHARP RISE IN UNSTEADINESS	MOST COMMON DEFINITION. PLASMA INSTABILITY LOCALIZED DOWNSTREAM
(b) INCREASED WALL EROSION	CLOSELY ASSOCIATED TO (a) CURRENT CONCENTRATIONS
(c) DEVELOPMENT OF LARGE ANODE DROP	NOT ALWAYS PRESENT. ALLEViated BY ANODE GAS INJECTION
(d) TRANSITION $V = I_p$ TO $V = P$	PROBABLY UNRELATED, BUT HAS BEEN ASSOCIATED WITH ONSET

- APPROXIMATE EMPIRICAL CORRELATION:

$$\frac{I_c^2}{m} \sqrt{M} \approx K \frac{I_p}{H}$$

I = CURRENT
 \dot{m} = FLOW RATE
 M = MOLECULAR MASS
 L = ACCELERATOR LENGTH
 H = INTER-ELECTRODE DISTANCE
 K = CONSTANT

EXPLANATIONS OF ONSET (NO COMPLETE THEORY)

DESIGNATION	BASIC ASSUMPTIONS	PREDICTIONS	COMMENTS
(a) EQUIPARTITION, OR CRITICAL IONIZ. VELOCITY	'ONSET' OCCURS WHEN $eV_t = \frac{1}{2} m_i c^2$	$\eta_{\text{FROZEN}} = 1/2$ $\frac{I^2}{m^4} = \frac{1}{16} \frac{eV_t}{\mu_0} \sqrt{\frac{2eV_t}{m_i}} \frac{W}{H^2}$ $(W = \text{CHANNEL DEPTH})$ $(H = \text{INTERELECTRODE DISTANCE})$	PROVIDES ROUGH CORRELATION OF MOST DATA
(b) ANODE DEPLETION	HALL AXIAL CURRENT FORCES PLASMA AWAY FROM ANODE. 'ONSET' WHEN $(n_e)_{\text{ANODE}} = 0$	$\frac{I^2 m_i}{m^4} = 945 \frac{e}{16} \frac{k}{\sigma \mu_0^2} (T_e + T_{e0}) \frac{L \cdot W^2}{H^3}$	APPROXIMATELY SAME DEPENDENCIES AS DATA. PRESUMPTION IS THAT ANODE SHEATH WILL BREAK DOWN
(c) FULL IONIZATION	ONE OF SEVERAL ANOMALOUS EVENTS OCCURS AS IONIZATION ENERGY SINK DISAPPEARS	$\eta_{\text{FROZEN}} = F(\text{GEOMETRY})$ $\frac{I^2}{m^4} = \frac{1}{16} \frac{eV_t}{\mu_0} \sqrt{\frac{2eV_t}{m_i}} \frac{1}{A^2} \frac{1}{C_0} \sqrt{\frac{3eV_t}{1 - \eta_{\text{FROZEN}}}}$ $W_s = \text{DEPTH AT INLET}$ $A^2 = W^2 H^2 = \text{THROAT AREA}$ $\eta_{\text{FROZEN}} = \frac{V_t}{V_{\text{MAX}}}$ $V_{\text{MAX}} = \text{VELOCITY FOR MOMENTUM} + \text{MAGNETIC FORCE}$	A VARIATION ON (a) PROVIDES MORE DETAIL. STILL NO MECHANISM
(d) INSTABILITIES	SEVERAL PROPOSED: - IONIZATION INSTAB. - MICROINSTABILITIES OF TWO-STREAM TYPE - STATIC ELECTROTHERMAL	INSTABILITY THRESHOLD (DEPENDS ON TYPE) - DOMINANT WAVELENGTH - FREQUENCIES - HEATING EFFECTS, ETC.	ELEC-TROTHERMAL INSTAB. PROVIDES MECHANISM FOR (c) MICRO-INSTABILITIES MAY EXPLAIN HIGH T_e ALL VERIFIABLE BY DETAILED PROBING

GEOMETRY EFFECTS ON ONSET

- BASED ON 1-D, VARIABLE AREA MODEL WITH P NEGLECTED. "ONSET" ASSUMED WHEN $V_1 \cdot \frac{1}{2} m u_1^2 = m e V/m_1$
- TWO CONTOURS: (a) CONSTANT AREA
(b) CONV. - DIV. (SPACING CHOSEN FOR CONSTANT CURRENT DENSITY)
- LENGTH MEASURED BY MAGNETIC REYNOLDS NÚ. BASED ON ALFVEN CRITICAL SPEED:

$$R_{m_A} = \mu_0 e V_A^* L \quad (V_A^* = \sqrt{\frac{2 e V_1}{m_1}})$$

- TWO MEASURES OF "ONSET"

$$(1) \text{ NORMALIZED } \frac{I^2}{m} \quad : Y = \frac{U_{ext}}{V_A^*}, \quad U_{ext} = \left(\frac{1}{2} \mu_0 \frac{A^2}{W_1^2} \right) B^2$$

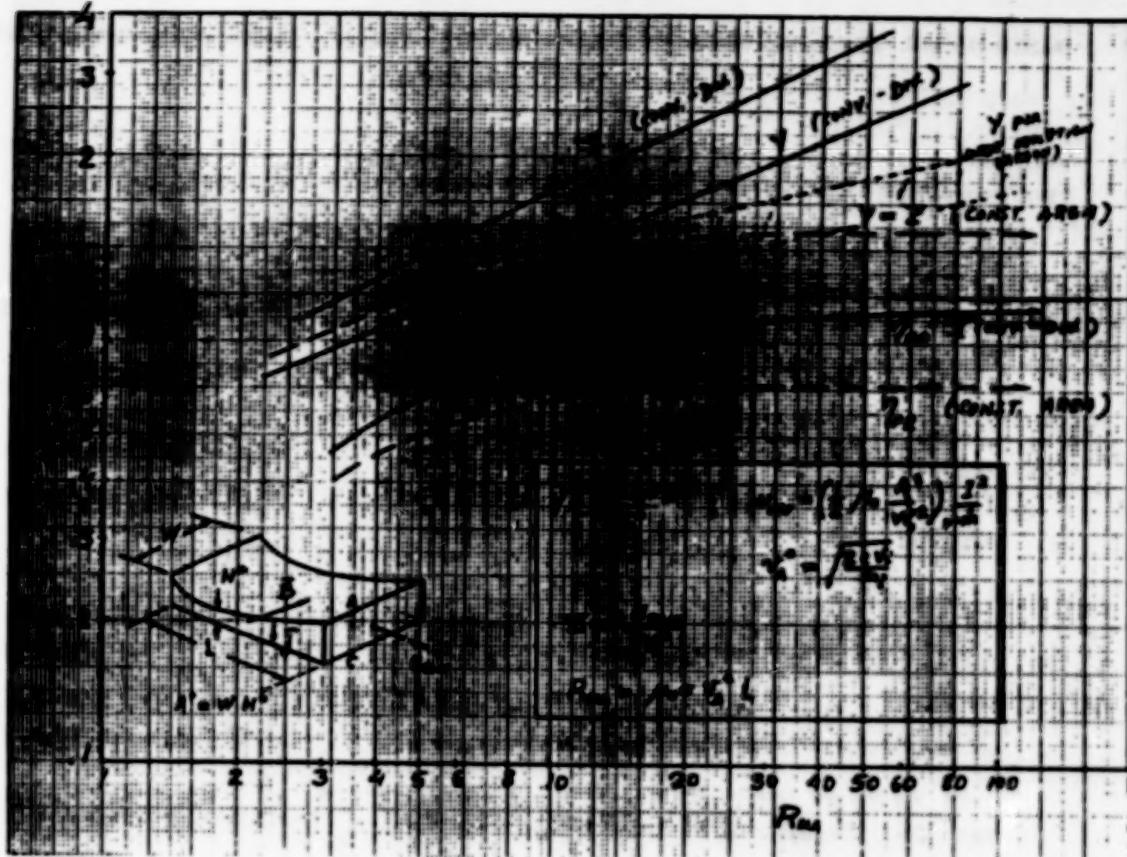
$$(2) \text{ NORMALIZED EXIT VELOCITY: } Z = \frac{U_E}{V_A^*}$$

- RESULTS SHOW SIGNIFICANT GAINS IN U_{ext} AND I^2/m BY CONTOURING
- BUT NO GAINS OF I^2/m - SHOWING LIMITATIONS OF $\frac{I^2}{m}$ PARAMETER
- GAINS HIGHEST AT LARGE R_{m_A}

ONSET AT FULL IONIZATION - CONSEQUENCES

- PREBLE'S WORK ON ELECTROTHERMAL INSTABILITY PREDICTS CORRECTLY SEVERAL TRENDS, INCLUDING DEVIATIONS FROM I^2/m RULE.
- ELECTROTHERMAL INSTABILITY SEEN TO OCCUR AT ≈ 0.9 ONLY. HOWEVER, 'FULL IONIZATION' IS NECESSARY FOR INSTABILITY, NOT SUFFICIENT.
 - (a) GROWTH MAY BE WEAK IN PASSAGE TIME
 - (b) IN SMALL CHANNELS OR AT LOW PRESSURES, DIFFUSIVE EFFECTS PROVIDE STABILITY
- THEORY STILL TOO CRUDE (LINEAR, CONSTANT BACKGROUND, NO ION DYNAMICS...)

HOWEVER, GIVEN ITS SUCCESS, IT IS INTERESTING TO EXPLORE CONSEQUENCES OF 'FULL IONIZATION' MODEL.



RELATIONSHIP TO ANODE DEPLETION

- ANODE DEPLETION LIMIT INCREASES ONLY WEAKLY WITH LENGTH (R_{MA}). HENCE, IF R_{MA} IS INCREASED IN ORDER TO GAIN EFFICIENCY AND I_{sp} , DEPLETION MAY HAPPEN BEFORE ONSET.
- THIS WAS CLEARLY OBSERVED IN OUR OWN TESTS. ALSO SEEN BY KURIKI ET AL. (AIAA-81-0683) IN KIII THRUSTER. HERE, A_V FIRST INCREASED GREATLY WITH CURRENT, THEN COLLAPSED AS ONSET FLUCTUATIONS OCCURRED.
- THE GRAPH ALSO SHOWS A BAND OF PREDICTED DEPLETION NORMALIZED $R_{MA}^{1/6}$ PARAMETER (Y) FOR ARGON. FOR H_2 , THRUSTERS MAY ENCOUNTER DEPLETION FIRST.
- NOTICE THAT (PARTICULARLY FOR CONSANT AREA), DEPLETION AND FULL IONIZATION HAPPEN (IN ARGON) AT ABOUT THE SAME TIME FOR THE IMPORTANT R_{MA} RANGE. THIS HAS BEEN NOTED REPEATEDLY, AND HAS BEEN A SOURCE OF CONFUSION.

SUMMARY ON SELF-FIELD MPD

- EFFICIENT ONLY AT HIGH POWER DUE TO LOW VOLTAGE, LARGE ELECTRODE LOSSES.
- HIGH POWER OPERATION LIMITED BY "ONSET"
- PHYSICS OF ONSET NOT YET CLEAR, BUT IT APPEARS TO DICTATE RATIO OF FROZEN LOSS TO KINETIC ENERGY. HOWEVER, THIS RATIO MAY BE CONTROLLED BY DESIGN.
- ANODE DEPLETION IS SEPARATE LIMITER, ESPECIALLY FOR LONG CHANNELS. SHOULD DESIGN FOR COINCIDENT ONSET AND DEPLETION (OR FIND WAYS TO REDUCE ΔV_{ANODE})
- LIFE ISSUES DIFFICULT, BUT PROGRESS IS ENCOURAGING
- SPECIFIC IMPULSE APPEARS SUFFICIENT IF USING H_2 OR L_i

APPLIED FIELD MPD - THE LOGICAL GROWTH PATH

- NO TECHNOLOGY FOR HIGH I_{sp} COMPACT THRUSTERS IN THE 50 - 100 KW RANGE
- AF - MPD POORLY UNDERSTOOD, BUT HAS SHOWN POTENTIAL TO FILL THIS ROLE. IN ADDITION, NO APPARENT HIGH POWER LIMIT (MAY BECOME SF AT HIGH POWER)

THE CASE FOR AF

A-PRIORI ARGUMENTS:

- (a) INCREASED IMPEDANCE DUE TO $U_0 B_z$ VOLTAGE LESSEN IMPACT OF ELECTRODE ΔV 'S - SHOULD ALLOW FOR POWER OPERATION.
- (b) PLASMA ROTATION REDUCES ELECTRODE DAMAGE BY ARCS OR OTHER FAULTS - MAY ALLOW POST-ONSET OPERATION.
- (c) MAGNETIC CONFINEMENT SHOULD HELP PROTECT WALLS - REDUCE WALL LOSSES, LENGTHEN LIFE.
- (d) MAGNETIC NOZZLE SHOULD ALLOW SOME FROZEN LOSS RECOVERY BY EXTERNAL EXPANSION.

THE CHALLENGES OF AF MHD

- (a) ADDED OPERATIONAL COMPLEXITY. BUT SEE RECENT WORK (TAIIARA ET AL., ARAKAWA ET AL.) SHOWING POTENTIAL FOR SERIES LOOPS OR PERMANENT MAGNETS.
- (b) INCREASED TESTING DIFFICULTIES (LONG MAGNETIZED PLUME). BUT LOW POWER OPERATION TO COUNTER.
- (c) GREAT PHYSICAL COMPLEXITY. THRUST - PRODUCING MECHANISMS STILL DEBATED. SPATIAL-TEMPORAL UNIFORMITY NOT GUARANTEED. REGIMES OF OPERATION UNCHARTED.

RECOMMENDATIONS

- REPRODUCE AND VERIFY SELECTED APPLIED FIELD MPD EXPERIMENTS FROM EARLY LITERATURE AND/OR FROM ABORAD.
- SUPPORT THEORY/MODELING WORK ON AF THRUSTERS TO EXPLOIT EXISTING COMPUTATIONAL CAPABILITIES.
- CONTINUE QUASI-STEADY SF AND AF TESTING TO STUDY DETAILED PLASMA MECHANISMS RESPONSIBLE FOR "ONSET" AND OTHER BULK EFFECTS.
- USE 100 - 500 KW STEADY STATE FACILITIES FOR
 - (a) STUDIES OF ELECTRODE LIFE AND THERMAL DESIGN FOR BOTH, AF AND SF THRUSTERS.
 - (b) PERFORMANCE MAPPING AND SYSTEM INTEGRATION FOR AF THRUSTERS.

S7-20

Appendix J

N92-10051⁴⁰⁰⁵³

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Department of Aeronautical and Astronautical Engineering
The Ohio State University

MACHETROPLAEMODYNAMIC ARCJET RESEARCH

PM 5/3/2008

NPO THRUSTER RESEARCH ISSUES, ACTIVITIES, STRATEGIES

Briefing at NPO Thruster Technology Workshop

16 May 1991

Washington, DC

Department of Aeronautical and Astronautical Engineering
The Ohio State University

MAGNETOPLASMADYNAMIC ARCJET PROPULSION

BRIEFING OUTLINE

RESEARCH ISSUES

- What are the development "opportunities" available to the MPD thruster for application to missions over the next decades?
- What's different compared to twenty years ago?
- How should we be approaching MPD thruster development?

RESEARCH ACTIVITIES IN THE OSU AAE DEPARTMENT

- What is happening now?
- What is becoming available?

RESEARCH STRATEGIES

- How do we safeguard an evolutionary program that can provide continual contributions to space activities, while responding to opportunities for an accelerated national commitment to space exploration?

NPD THRUSTER RESEARCH ISSUES

EFFICIENCY

- Promise of NPD thruster is that it is a very robust system that can handle high power levels, while delivering high specific impulse. This does not relieve it of a cost-per-ion efficiency penalty at lower specific impulse values. The robustness of an NPD thruster compared to an electrostatic device derives fundamentally from the use of Hall electric fields instead of accelerating grids.
- Any process that requires more energy per ion than the minimum value can be regarded as an inefficiency of the ionized-propellant system (including the electron flow needed to neutralize the propellant). In NPD ~~in~~ electrostatic thrusters, the ion source and neutraliser are presently coupled very closely to the accelerator system. We have historically accepted the gas discharge and electrode processes provided by particular devices, and pressed on with performance studies.
- An additional efficiency factor that has received inadequate attention is simply the directedness of the exhaust flow. There are two considerations here: direction of the accelerating force field, (akin to concern for beam optics in electrostatic thrusters); and collimation of the exhaust flow, including the notion of obtaining additional thrust kinetic energy from plasma internal and/or rotational energy.

MHD THRUSTER RESEARCH ISSUES (continued)

HIGH SPECIFIC IMPULSE

- The principal concerns here involve the possible limitation of practical specific impulse due to the "onset" of difficulties in the MHD thruster. These difficulties include, to varying degrees in different devices: increased frozen-flow loss, and increased losses at the anode, the cathode, and insulator surfaces. The latter category of losses also afflict the thruster in terms of lifetime and thermal management.
- There are many theories providing explanations for "onset". A reasonably common element in these theories is the association of higher specific impulse with lower particle densities in the MHD discharge. At lower densities, the discharge is:
 - a) Depleted of sufficient charge-carriers near an electrode, leading either to sheath or hydrodynamic instabilities;
 - b) Depleted of sufficient charge-carriers within the plasma, permitting the growth of various drift instabilities;
 - c) Deprived of sufficient energy sinks to absorb, in a uniform manner, the dissipation demanded by steady, electromagnetic acceleration.
- While "onset" can adversely affect the efficiency and lifetime of MHD thrusters, the momentum equation for electromagnetic acceleration must still be satisfied. Deviations from expected performance in terms of thrust and/or exhaust speed must be examined, particularly at low densities, for the effects of viscous drag, and mass addition (associated with "onset" processes); an additional concern is gross distortion of the discharge pattern, e.g., spoking or filamentation.

NPO THRUSTER RESEARCH ISSUES (continued)

LIFETIME AND SYSTEM PERFORMANCE

- Inefficiencies injure thruster performance in three ways: increased power system to obtain the desired output; increased thermal management to handle loss; and reduced component lifetime.
- It is a system issue to select the optimum operating values for intensive properties, such as current density, traded against component efficiencies and lifetimes. Research/development tasks and system designs must be consistent. To provide input to system trades, component development and lifetests are, therefore, very important (even if we still prefer, and require, full system tests in an accurate environment).

MHD THRUSTER OPPORTUNITIES

BASIC APPROACH

IF YOU DON'T LIKE IT, FIX IT !

- Theories indicate that there are physical causes for difficulties in MHD thrusters. They also imply solutions based on proper choices of operating regime and device geometry. We must be prepared to change geometric arrangements as we change terminal properties. This includes adjusting the relative magnitudes and directions of applied and self-magnetic fields.
- Some components, such as electrodes, may never perform adequately while incorporated automatically as part of the main thruster flow channel. We need to invent components that satisfy their special performance requirements. (We didn't require the ion source in an electrostatic thruster to be a flat plate, so why must the cathode be a simple, solid cylinder?)

MHD THRUSTER OPPORTUNITIES (continued)

BRIEF EXAMPLES OF DIRECTIONS FOR DEVELOPMENT

Overcoming "Onset"

Principal difficulty may derive from excess dissipation deposited in too few particles. Solution lies in minimizing dissipation per unit volume, i.e., lowering the current density and increasing the particle density.

For constant area channels at high magnetic Reynolds number, the thickness of the current conduction zone scales as:

$$d = 1/\sigma \mu u ,$$

where σ = electrical conductivity
and u = flow speed

Typically, microturbulence becomes important when the drift speed for the electrons, carrying the current, exceeds some speed, such as the ion thermal speed. In terms of the total current J and mass flow rate \dot{m} , the electron drift speed scales as:

$$v_{de} = K J / n_e e (2 \pi r d)$$

$$= K \sigma u^2 J \dot{m} / \dot{m} ,$$

where K = a scaling constant
 n_e = electron density
 r = channel radius
and \dot{m} = channel height

MHD THRUSTER OPPORTUNITIES (continued)

Overcoming "Onset" (continued)

If the flow speed is determined by the electromagnetic thrust, so $u = g J^2 / \dot{m}$, then:

$$v_{de} = K \sigma u^3 h / gJ$$
$$= K \sigma h g^2 J^5 / \dot{m}^3$$

This suggests that, while we should expect microturbulence to be more important at higher specific impulse, we can mitigate the situation by increasing the current at the desired exhaust speed. Narrower channels also improve the flow by increasing the mass density at a given flow rate.

Furthermore, it should be noted that the scaling of current conduction thickness with magnetic Reynolds number did not account for varying channel height, which can reduce the current density considerably, thereby decreasing the required drift speed.

MPD THRUSTER OPPORTUNITIES (continued)

BRIEF EXAMPLES OF DEVELOPMENT DIRECTIONS

Improving Electrode Performance

Hollow Cathode vs Solid Cathode:

It has been a reasonable notion for some time that the performance of a cathode could be improved considerably if we could control the environment of the cathode, rather than merely submit it to the bombardment of whatever flow field and species were provided by the thruster channel itself. This notion, while seductive, has tended to founder on our inability to predict and design hollow cathodes that actually function as such over all ranges of desired operation. For example, the simple interplay of cathode fall voltage and a resistive voltage drop of comparable magnitude within the hollow cathode can preclude significant incursion of the current. Theory indicates, however, that proper operation can be obtained by varying the scale size, while matching the current and mass flow rate. Successful operation would offer the opportunity to increase the available emission area, while maintaining the effective cathode radius, and also to reduce losses due to processes such as evaporation and plasma radiation.

Anode Shaping:

Historically, we have measured and accepted the current density, and associated flow pattern, in the vicinity of the anode. Yet, we may expect for a magnetized plasma flow at high magnetic Reynolds number that two-dimensional expansion at the exit of the thruster will result in current concentration at the anode lip. Such concentration, combined with reduced particle density, may result in plasma processes that enhance losses near the anode. Furthermore, the rather abrupt expansion presently available to the magnetized plasma flow provides a significant non-axial component to the exhaust flow. It should be possible to design the anode shape, both to ameliorate problems associated with current concentration, and to improve the thrust efficiency in terms of flow direction.

MHD THRUSTER OPPORTUNITIES (continued)

BRIEF EXAMPLES OF DEVELOPMENT DIRECTIONS

Applied Fields to the Rescue

Applied fields are not a panacea, but they are not anathema either.

Impedance Enhancement:

At lower power levels, the back EMF available in self-field MHD thrusters is simply too small to compete effectively with the voltage drops required near electrodes, so the efficiency will automatically suffer. Addition of a solenoidal field (rz -plane) provides several mechanisms that can increase the voltage across the plasma, including Hall electron flow (increases resistance), plasma rotation (homopolar motor), and direct interaction of discharge or induced currents with applied field components (linear motors). At fixed total power, while the efficiency may improve with higher discharge voltage, the total current must decrease, resulting in insufficient current density to achieve diffuse discharge.

Discharge Control:

By shifting the direction of net current flow, the addition of solenoidal fields can alter the physical scale lengths associated with dominant modes of some plasma instabilities, and perhaps create sufficient "shear" for actual stabilization. Often, however, the plasma simply becomes unstable in other directions. An increase in azimuthal current density (Hall current), for example, again offers the opportunity for drift instabilities. If we have too much dissipation chasing too few particles, without other mechanisms (e.g., heat transfer) available to diffuse this energy, we can have instability growth. ('Inflation economics for plasma electrons').

In the simplest notion, the applied field "swirls" the plasma to smooth out nonuniformities (especially near electrodes. Azimuthal variations have nevertheless been observed in some devices.

MPD THRUSTER OPPORTUNITIES (continued)

Applied fields (continued)

Flow Control:

Solenoidal fields can be used to guide the flow, in the manner of a solid nozzle, and thereby improve thrust efficiency simply by achieving more collimation. In principle, the proper variation of applied field with position can also contribute to control of the current distributions on electrodes. There is also the possibility of converting plasma rotational energy and internal energy to thrust energy. For a fluid plasma, the control of the flow, including energy conversion, is accomplished through pressure gradients, so we must be careful not to lose energy via internal states in a hypersonic flow interaction. For a collisionless plasma, the behavior is more complicated, including non-adiabatic transitions and cross field drifts.

MPD THRUSTER OPPORTUNITIES

WHAT'S DIFFERENT COMPARED TO TWENTY YEARS AGO ?

- Computational fluid dynamics has finally penetrated to the MPD thruster community.

We can now do the arithmetic for two (and a half) dimensional electromagnetically-accelerated plasma flows. This permits us to examine concepts, design experiments, and interpret data (including interpolation between regions of available measurement, and inference of quantities we couldn't measure). We can also use experimentally validated computational tools to provide scaling relations for component and system development.
- Computer-assisted diagnostics allow us to gather and manipulate data that the plasma has always offered, but that has required too much effort to convert to physically-useful information, (e.g., spectral lineshapes for velocity distributions).
- We've been around the block before.

RESEARCH ACTIVITIES IN THE OSU AAE DEPARTMENT

WHAT'S HAPPENING NOW ?

Magnetic nozzles, Hollow cathodes, Anodes, Plasma studies

Support	Student	Activity
AAE	H. Kanhawi	Construction of high power facility; high power, applied field studies.
NASA LeRC APOSRR	N. Kiristis	Thomson scattering in magnetic nozzle exhaust; laser interferometry.
AAE	K. Li	Construction of high power facility; high power, applied field studies.
NASA LeRC AAE	P. Nikellides	Numerical computation of MPD and magnetic nozzle flows; non-equilibrium plasma flows.
AAE	A. Salhi	Theoretical and experimental electrode studies; hollow cathodes.
AAE	T. Shannon	Experimental modeling of space plasma environment.
NASA LeRC	G. Soulas	Magnetic nozzle effects on a scaled MPD thruster.
NASA LeRC	T. Umeki	Spectroscopic analysis of magnetic nozzle flows; electrode heat transfer.

RESEARCH IN THE OSU A&E DEPARTMENT

FACILITIES AND APPARATUS

WHAT'S THERE NOW ?

- Plasma sources: Quarter-scale MPD thruster, Ablative thruster, Space physics source.
- Power sources: Thruster PFM (2.3 kA, 300 usec)
Nozzle PFM (2.7 kA, 500 usec).
- Diagnostics: Electrostatic and magnetic probes,
Laser scattering - Ruby (10 J)
- Glass (60 J)
Laser interferometry and long wavelength
scattering - CO₂ (60 w)
Spectroscopy (0.25 and 0.5 m).

WHAT'S BECOMING AVAILABLE ?

- Very high power facility ("Godzilla")
400 kA, 2 msec (from a 5 MJ capacitor bank PFM)
- High power, steady arcjet
1 Megawatt, 60 sec burst-mode operation
(presently running on air at 10 atm)

RESEARCH IN THE OSU AAE DEPARTMENT

WHAT'S HAPPENING NOW ?

-- MACH2 computer code being transferred from Phillips Lab (Albuquerque) to Cray-2 at NASA LeRC.

MACH2 is a 2-1/2 dimensional (includes axisymmetric rotation), MHD code developed originally to model very high power (1-100 TW) plasma accelerators at the Air Force Weapons Lab (now Phillips Lab). The code employs an ALE procedure with a convenient block-based computational grid to handle complex flow geometries. MACH2 uses a variety of equation of state packages, such as the LANL SESAME tables, and, more recently, nonequilibrium models allowing separate constituent temperatures. It also includes phenomenological models for anomalous transport based on microturbulence. Both self-field and applied fields are treated.

MACH2 has successfully modeled the plasma flow switch experiments at AFWL, and very low density, plasma switching in particle-beam diodes at Sandia Labs. It has also recently been applied to self-field MHD thruster experiments at R & D Associates. Presently at Phillips Lab, MACH2 is being used to model compact toroid experiments.

We will be working to make MACH2 an effective tool for MHD thruster development. This effort includes addition of appropriate "wall physics" and plasma modeling to compare with experimental results, in particular, the data base on applied-field thrusters generated at NASA LeRC, and magnetic nozzles at OSU. With validation, the code should be a useful contribution to the entire MHD thruster community.

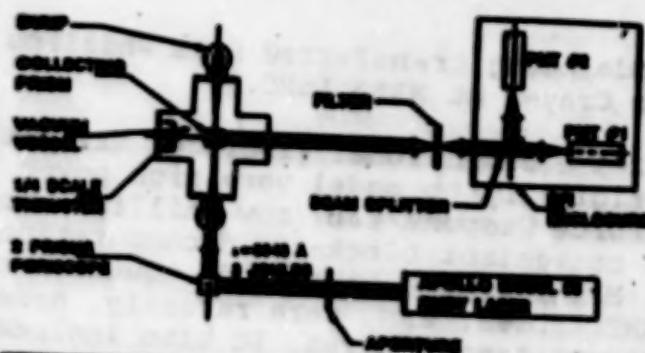


SPACE PROPULSION TECHNOLOGY DIVISION

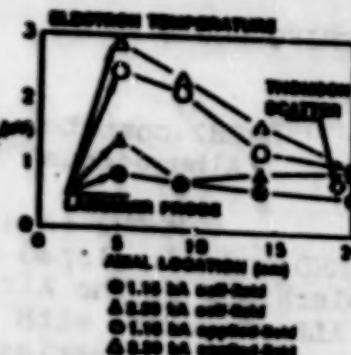


ADVANCED PROPULSION TECHNOLOGY (OSU) MAGNETIC NOZZLE RESEARCH AND TECHNOLOGY

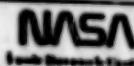
THOMSON SCATTERING SCHEMATIC LAYOUT:



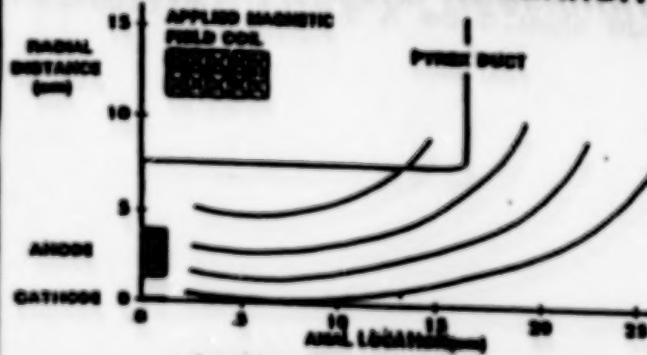
- Proof-of-Principle Thomson Scattering measurements (non-intrusive, not B-Field sensitive) successfully carried out for first time.
- Thomson Scattering results at 2.3 kA, applied B agree with Langmuir results corrected for finite current and B Field.



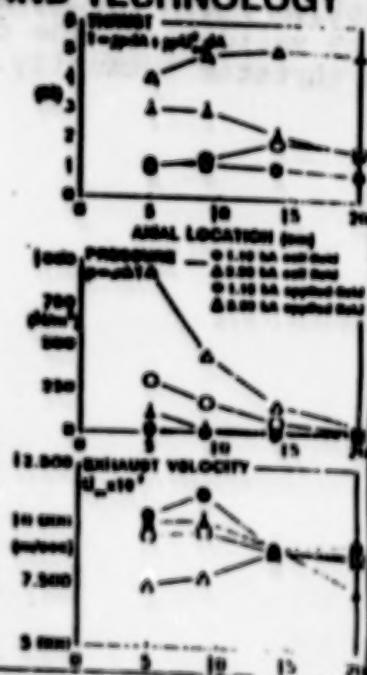
SPACE PROPULSION TECHNOLOGY DIVISION



ADVANCED PROPULSION TECHNOLOGY (OSU) MAGNETIC NOZZLE RESEARCH AND TECHNOLOGY



- Self-Field plasma expands to low pressure in 8 cm (plasma in test). Applied-field plasma expansion is controlled and has large μ pdA thrust.
- Applied fields can be optimized for Uex max or high thrust with low Uex. This will allow optimization of Uex for mission requirements.



RESEARCH STRATEGIES

HOW DO WE SAFEGUARD THE EVOLUTIONARY DEVELOPMENT OF NPD THRUSTERS, WHILE RESPONDING TO NATIONAL INITIATIVE FOR SPACE EXPLORATION ?

- Let's recognize the danger of debauching technology development programs that can contribute to near term, lower power missions (consistent with near term power sources), to develop the fully demonstrated capability for high power missions.
- Similarly, let's recognize that without some adequate promise of thruster performance at high powers, we may never (in our lifetimes) see the space-power systems needed for high energy missions. The driver is thrust power, not power on station, so the only incentive for developing high powers ($>10^3$'s- 100^3 's of Nw) in space is the enabling interest of the thruster.
- Furthermore, since the task of developing the desired space-power system is quite formidable, and therefore expensive, we cannot ignore those moments when the national will may support the cost. (In 1960, if we had turned from manned space exploration, because system studies indicated there was no real technical advantage, then Apollo would not have occurred, and there probably would not have been a significant space program.)

RESEARCH STRATEGIES

HOW DO WE PROCEED ?

- The principal driver is the expected funding profile. For a major new initiative that will be sustained into the out-years, there is a challenge to ramp-up to spend the available resources. We would probably not shrink from such a challenge. Some money would be wasted, but we could envision a forced development march that would tackle problems at high power, and answer questions as they manifested themselves in melted electrodes or tanks.
- Within a more realistic funding scenario, we need to proceed to establish a record of accomplishment and demonstrated capability. This is already occurring in terms of the evolution from low to higher power arcjets. The demonstration of higher power capabilities has four benchmarks still to achieve: efficiency, specific impulse, high power operation, and lifetime.
- We will not achieve these benchmarks, in a reasonable time, even in a minimal way commensurate with the budget, unless the following tasks are accomplished:
 1. Increase the discharge voltage relative to the electrode voltages.
 2. Control the plasma flow in terms of both its behavior within the accelerator, and its outward direction.
 3. Demonstrate at all levels of power appropriate to SEI, so that we are recognized as a continuing player. Such demonstration clearly has to become more faithful to the system environment as the mission application draws near.
 4. Demonstrate as much as we can, within budget limitations, so that at least lifetime questions on critical components can be answered. We fired rocket engines into atmosphere, and gained knowledge about combustion instabilities in large engines, long before we were able to test at altitude.

RESEARCH STRATEGIES

SHOULD THE PROGRAM BE BIFURCATED ?

"To \vec{B} , or not to \vec{B} ?"

- Bob Jahn, 1965

ARE THERE TECHNICAL REASONS THAT PRECLUDE COMMONALITY BETWEEN LOW AND HIGH POWER MPD ARCJETS ?

-- Easy answer: Yes. The lower power arcjets have too much of their energy economy tied up in electrode losses to be relevant to high power devices for which such losses, in principle, are negligible. To the extent that a variety of instabilities, not to mention mass addition phenomena, depend on energy available in non-directed forms, even basic behavior may vary substantially from sub-megawatt to multi-megawatt operation.

-- More challenging answer: No. To find application in near term missions, the lower power thrusters must become more efficient. This requires that the relative electrode voltages become small in low power devices. Apart from reducing the electrode voltages by inventing better arrangements, we must increase the discharge voltage. This demands that the discharge operate properly at lower currents, which directs our attention to conditions that determine discharge uniformity. Such conditions, and their relation to physical scale sizes, may be commensurate across the total operating range of interest. (For example, critical wavelength λ distance along current flow direction.)

Furthermore, it may be appropriate for all MPD thrusters to incorporate magnetic nozzles for improved thrust efficiency. Thus, the presence of applied magnetic field components becomes a matter of degree and optimization.

MHD THRUSTER RESEARCH AND DEVELOPMENT

SUMMARY

ACTIVITIES AND PLANS IN THE OSU AAE DEPARTMENT

- Experimental and theoretical research on magnetic nozzles at present and higher power levels; MHD thrusters with applied fields extending into the thrust chamber; improved electrode performance (e.g., hollow cathode)
- Tools
 - MACH2 code for MHD and nozzle flow calculation;
 - Laser diagnostics and spectroscopy for non-intrusive measurements of flow conditions (e.g., particle temperatures, fluctuations);
 - Extension to higher power (Godzilla, burst-mode arcjet at OSU, and cooperative experiments at NASA LeRC).

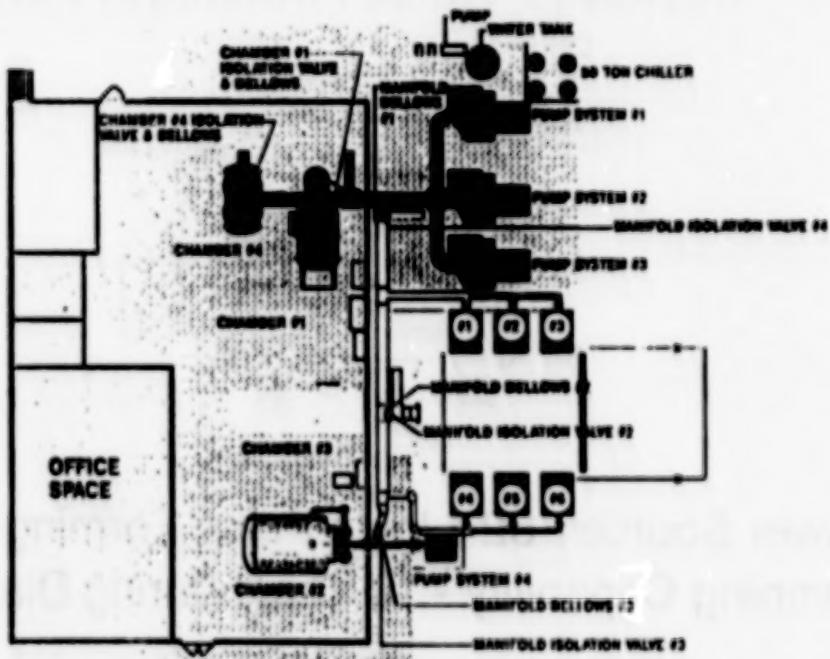
NATIONAL STRATEGIES

- Make the next steps beyond the experimental and theoretical base to demonstrate improved performance based on optimizing geometry for terminal values. Numerical modeling with validated code(s) is critical here.
- Demonstrate whatever we can across the full spectrum of SEI mission interest to be a major and continuing player. Allow fidelity for full system life test to be modulated by mission immediacy and dollars. Test component lifetimes to support development efforts and system studies.

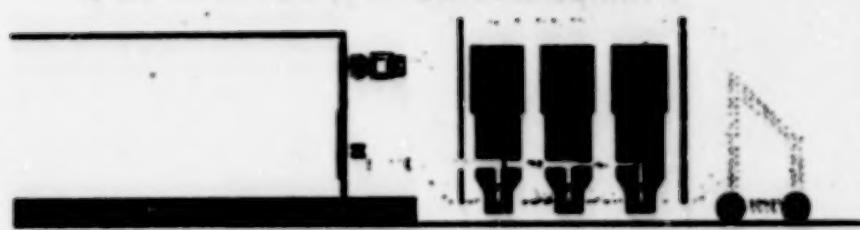
MPD Experimental Facilities

Phillips Laboratory, Edwards AFB

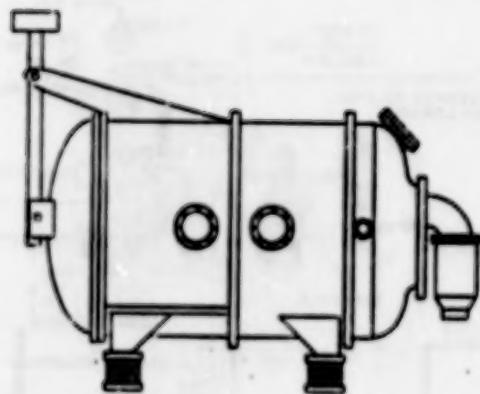
Electric Propulsion Facility Layout....



Steady State MPD Facility....



Pulsed MPD Facility



Power Source - 32 kJoule Pulse Forming Network
Pumping Capability - 10^{-4} Torr During Discharge

Schedule:

Quasi-Steady State MPD Facility - Apr. 1991

Steady State MPD Facility - Sep. 1992

OMIT
320

Appendix L



Air Force Steady State MPD Thruster Development

MAJOR WAYNE SCHMIDT



Steady State MPD Thruster Development....

PERFORMANCE GOALS:

- 1800 Seconds Specific Impulse
- 50 Percent Efficiency
- 100 kWe Power Regime
- 2000 Hour Lifetime

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Steady State MPD Thruster Development....

PROGRAM APPROACH:

Develop a Wire-Fed, Alkali Metal Fueled Thruster Where the Fuel is Supplied Through Dispenser Anodes and Cathodes. Potassium is Proposed for Earth-Orbit Transfers and Lithium is Proposed for the Mars Mission

ADVANTAGES:

- Operation Above Onset May Now be Desirable to Erode Sufficient Propellant
- Large Differences Between First and Second Ionization Potentials
- Phase Change and Low Work Function Reduce Cathode Temperature
- Low Melting Point Enables Warm Water Vacuum Pumping
- Replenishable Electrode Surfaces Eliminate Erosion
- Dispenser Anode May Eliminate Anode Starvation
- No Liquid or High Pressure Propellant Storage
- May Provide Additional Reactor Shielding

Steady State MPD Thruster Development....

SPECIFIC ISSUES:

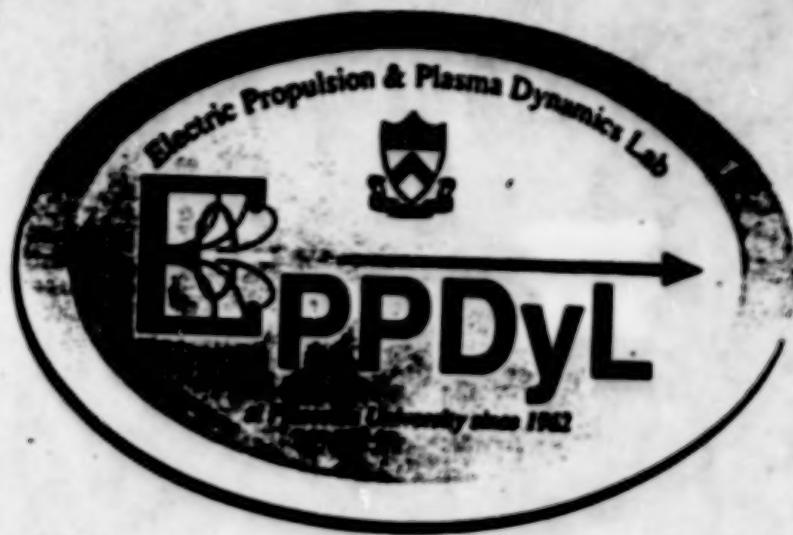
- PERFORMANCE EXPECTATIONS/VERIFICATION
 - Already Addressed
 - Continuous Life Test
- UNAMBIGUOUS QUASI-STEADY STATE/STEADY STATE DATA CORRELATION
 - Can't Be Done
- CRITICAL DESIGN PARAMETERS
 - Use of Propellant for Electrode Protection
- MINIMUM FACILITY REQUIREMENTS
 - Thrust Stand, 10^{-4} Torr, Wall Interactions Verified as Negligible, Automated
- INEXPENSIVE PUMP SCHEMES
 - Warm Water Pump With Propellant Recirculation (Alkali Metal Propellant)

Appendix M

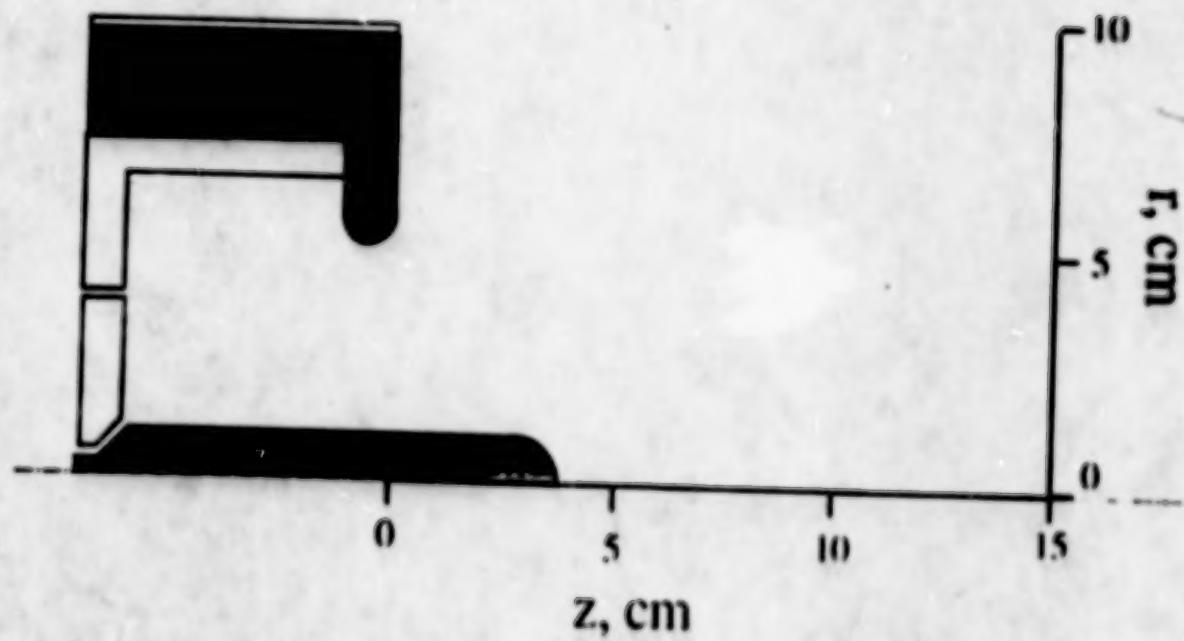
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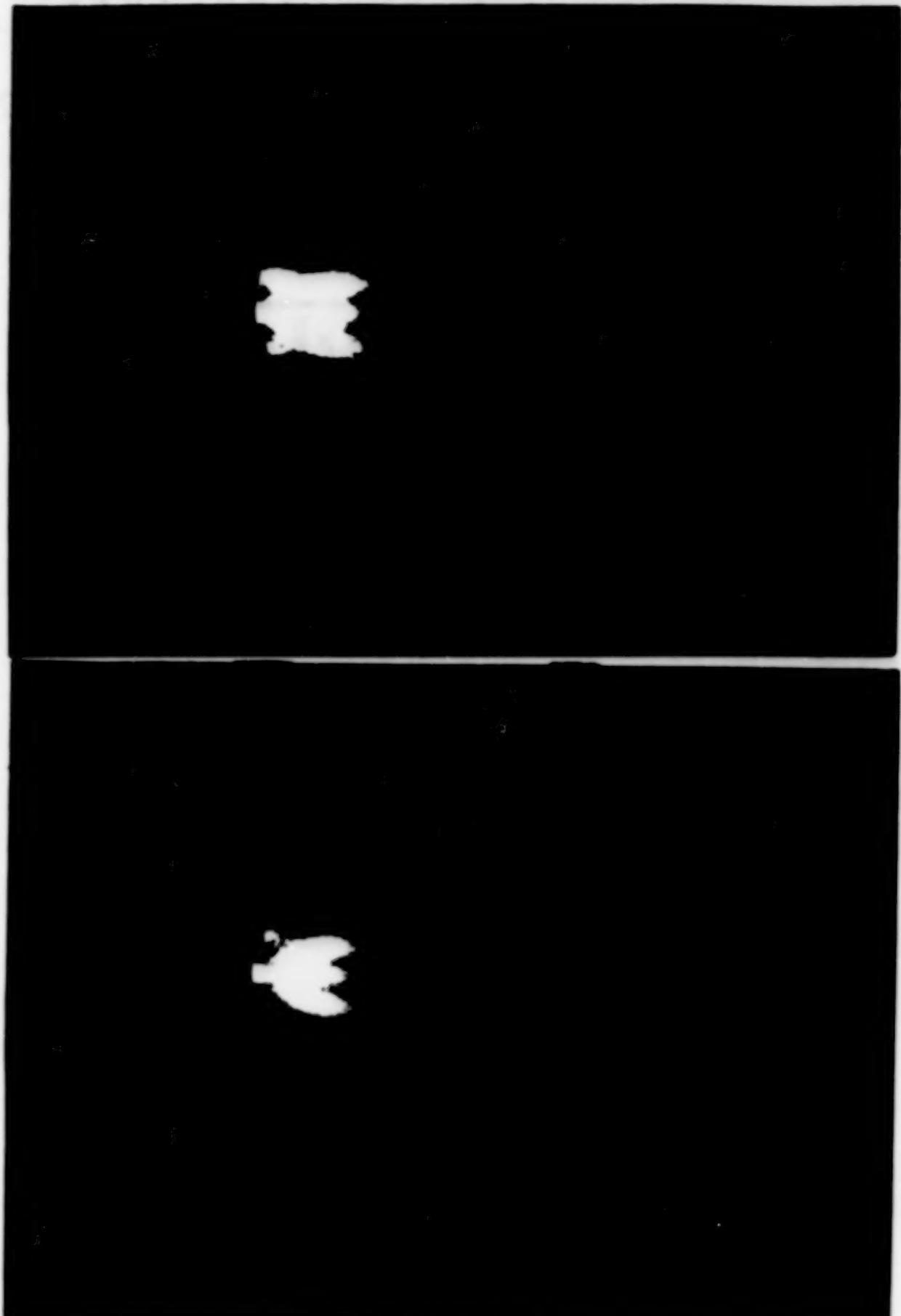
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M-2

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RESEARCH FOCUS

-2kW to -30 kW

- Anode losses are dominant
- Frozen flow losses are present
- Cathode erosion is important

-30 kW to ~ 200 kW

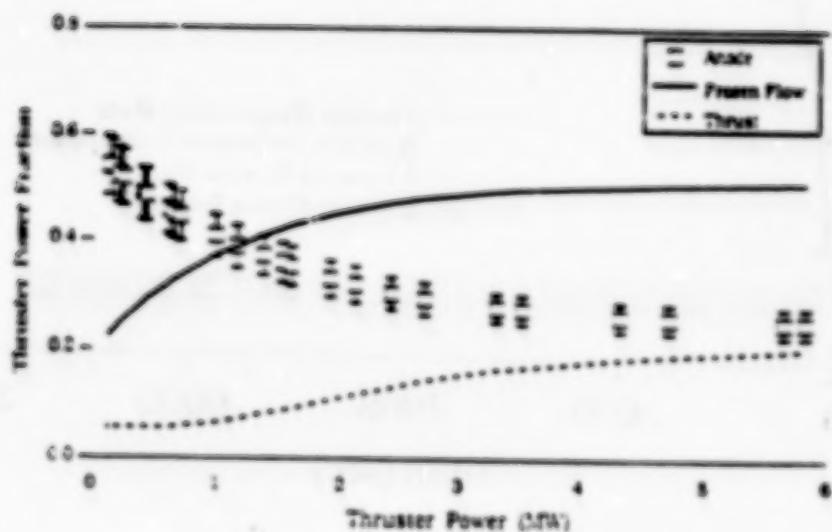
- Anode losses are important
- Frozen flow losses are important
- Cathode erosion is important

≥ 200 kW

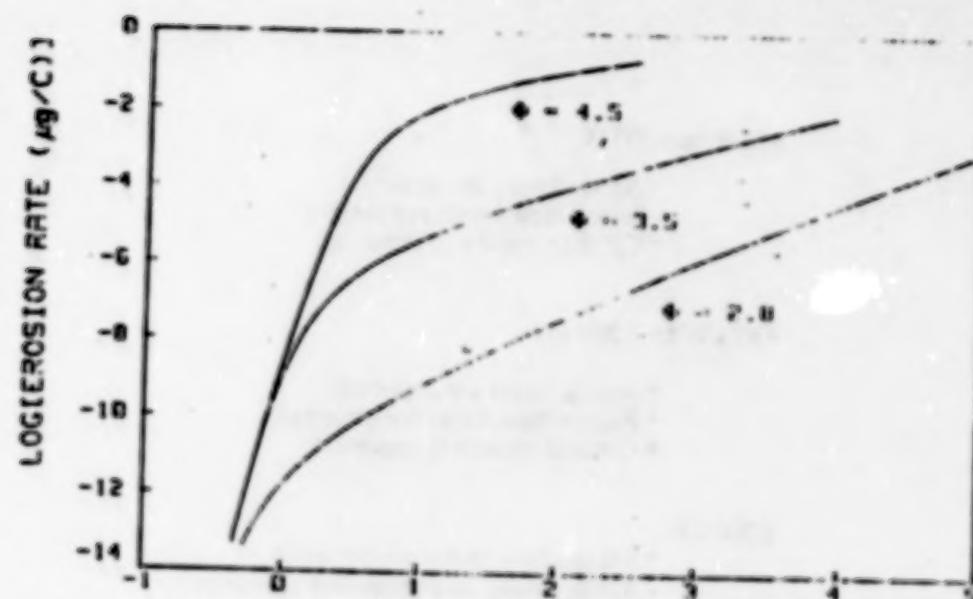
- Frozen flow losses are dominant
- Anode losses: an engineering challenge
- Cathode erosion is important

Presented at NASA '91

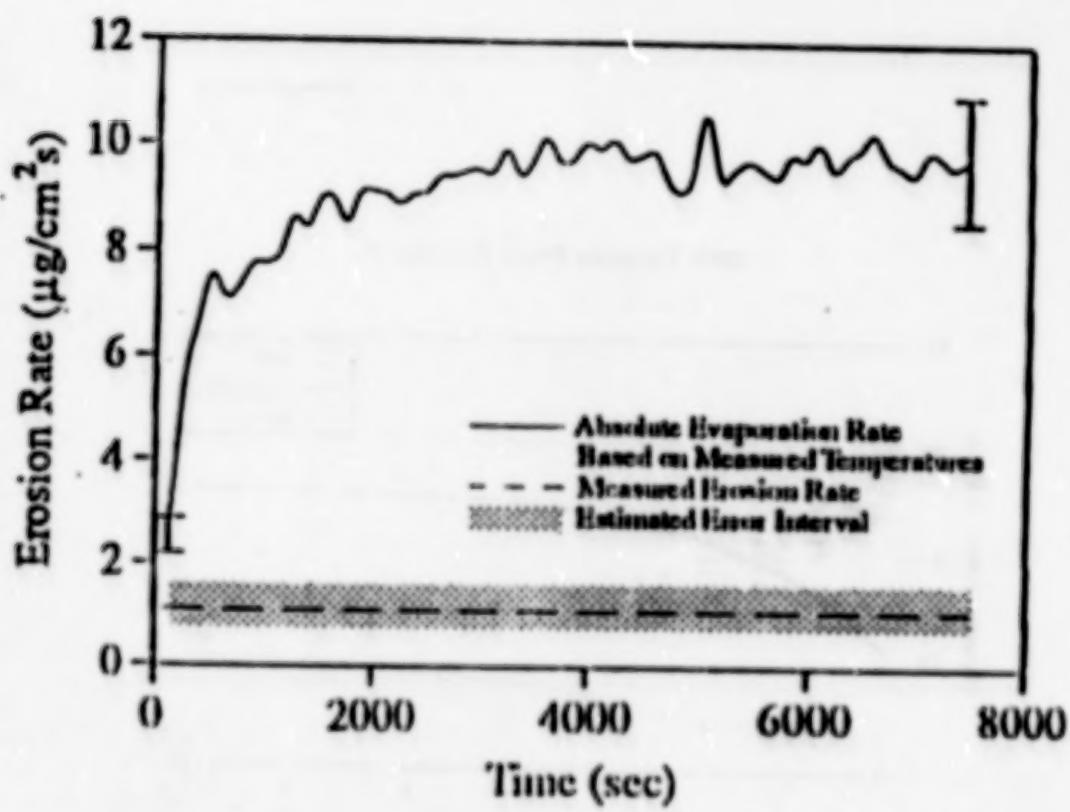
MPD Thruster Power Partitioning

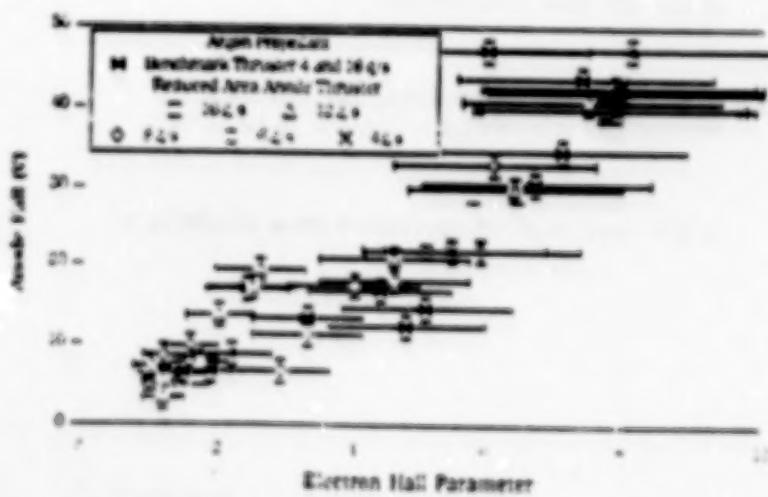
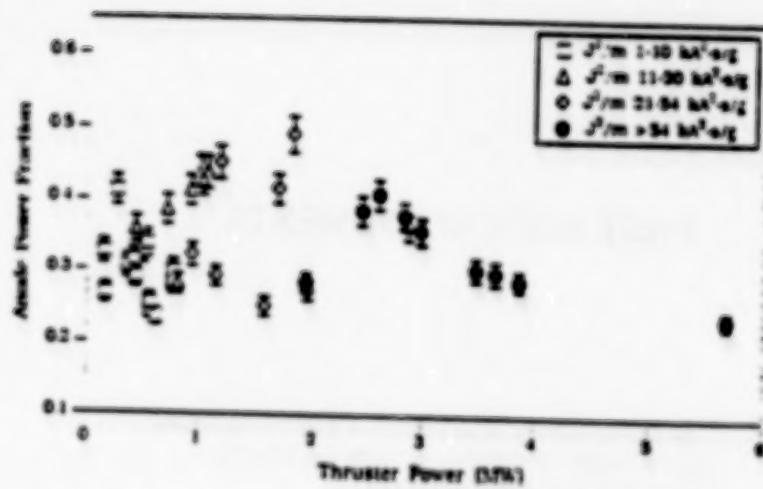
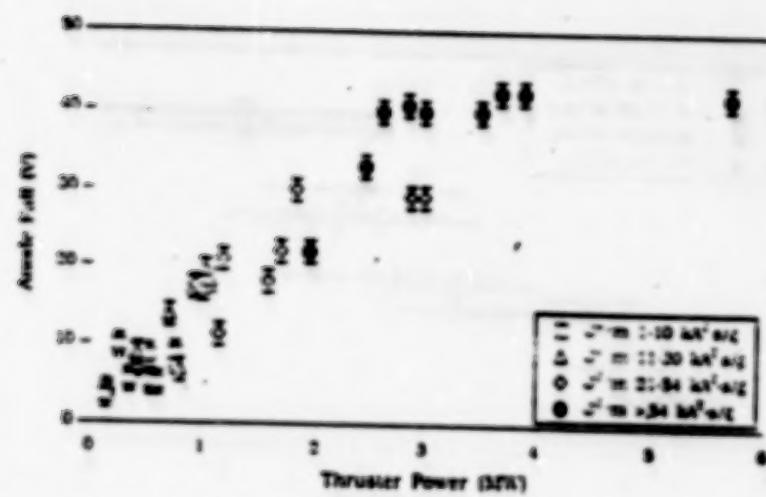


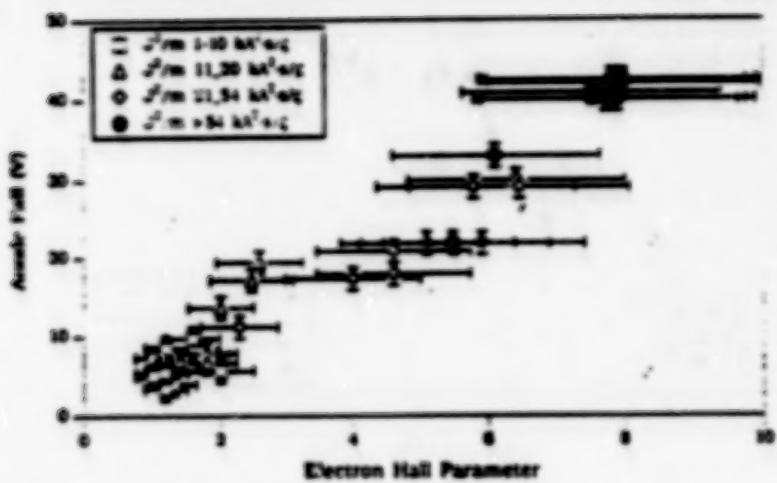
CATHODE EVAPORATIVE MASS LOSS



LOG(EROSION RATE ($\mu\text{g}/\text{C}$))







PAST ACCOMPLISHMENTS

1. Detailed kinetic description of electro-static and electromagnetic stability of current-carrying, collisional and flowing plasma.
2. Dispersion tensor reveals dominant unstable modes of the self-field MPD thruster.
3. Experiments confirm linear current-driven instabilities at levels below "critical" total current.
4. kW-level experiments confirm these instabilities.

CURRENT RESEARCH

- 1. Estimations of momentum and energy exchange rates between particles and unstable waves.**
- 2. Improved transport models include plasma turbulence effects.**
- 3. Numerical model (2-D MHD vectorized code) of MPD thruster.**
- 4. Evaluation of turbulence suppression by:**
 - a. Propellant choice and seeding**
 - b. Better magnetic field topology**
 - c. Geometry-induced scaling of current density**
 - d. Active radio frequency turbulence suppression**

Version 2P R1 MAY 71

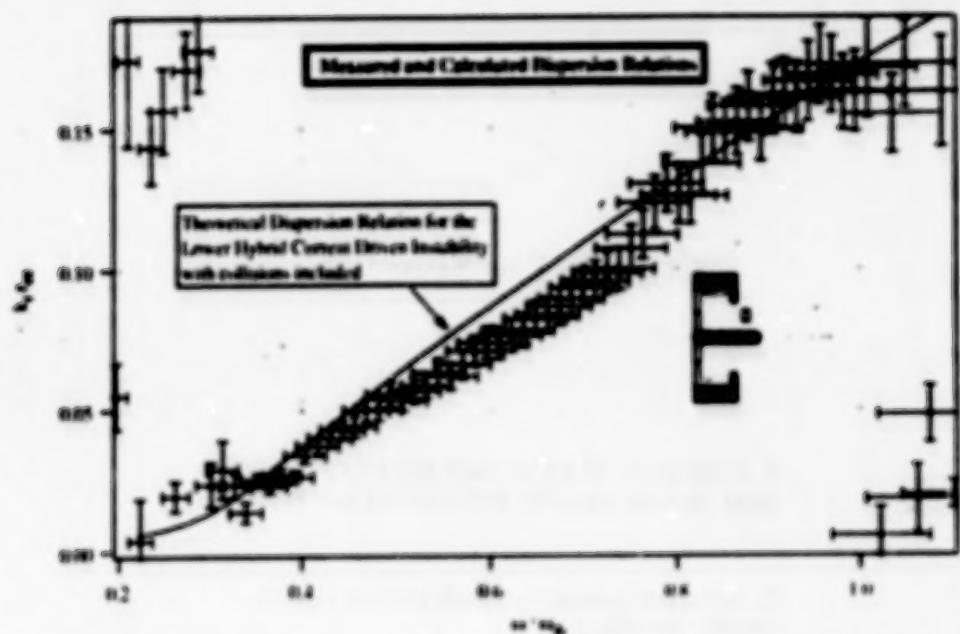


Figure 11 (b) 1000

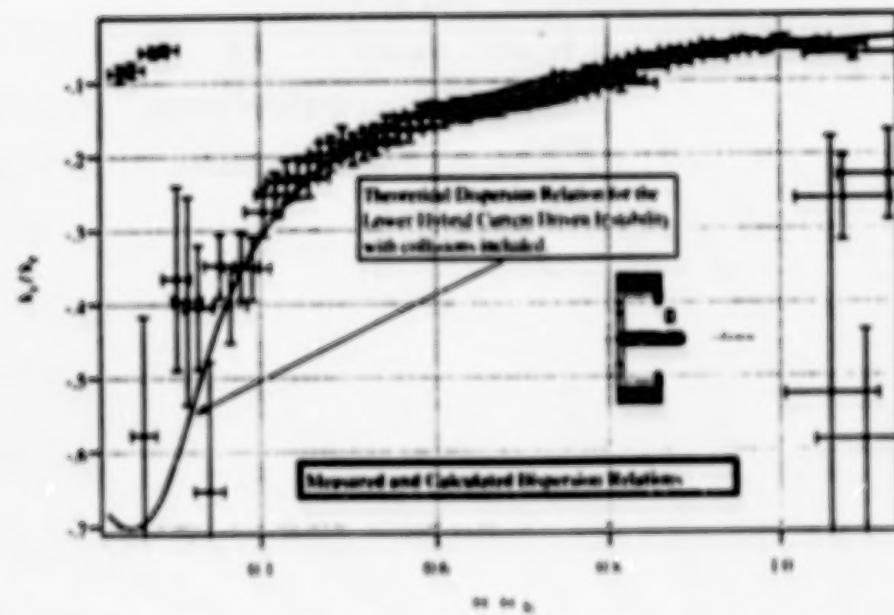


Figure 11 (b) 1000

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MPD Thruster Technology Workshop

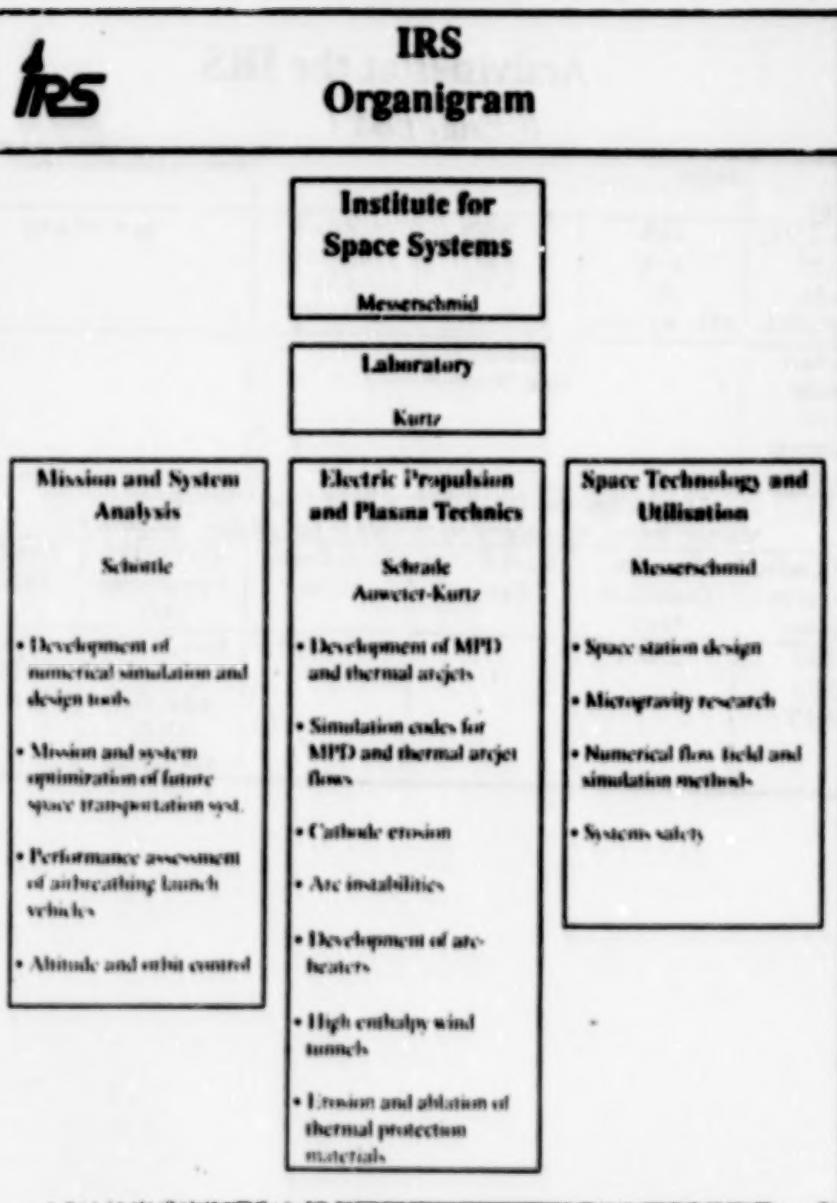
NASA HQ, Washington D.C.

16 May 1991

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IRS Presentation

E. Messerschmid



Electric Propulsion and Plasma Wind Tunnel



Activities at the IRS

May 1991

Activity / Thruster	MPD (Selffield)	Arcjet			Reentry (Material-Tests)	Missions, Trajectories
Power Level	100 kW-1 MW	1 kW	< 20 kW	< 100 kW	$h_0 < 10^8 \text{ J/kg}$	
Isp [km/s]	10 - 20	5 - 6	< 10	10 - 15		
Thrust [N]	5 - 20	0.1	> 1	> 10		
Propellant	Ar, N ₂ , H ₂ , NH ₃	NH ₃ , H ₂ , N ₂ , H ₂	N ₂ , H ₂ , H ₂	NH ₃ , H ₂		
Theories	Flowfield Stability Arc- Attachment Erosion	Constrictor Flow Heat Transport				Traject. - Optimizat.
Diagnostics	Emission Spectroscopy, el. Probes, Fabry-Perot Interferometry, Mechan. Probes, Mass Spectroscopy, Optical Temperature Measurement					
Status	Water Cooled Laboratory Devices	Radiation Cooled Lab. Model	Water Cooled Devices	Water Cooled Devices	PWK1 - IRS Operat. since 1987	PWK2 - IRS Operative
Contractors	USAF DFG BMFT	DARA		NASA (IST)	ESA / CNES, AMD-BA, AS, SEP, DO, MBB, MAN, DLR	DARA SFB ESA, FGE



IRS Facilities

High DC Power Supply:

Power: ≤ 6 MW
Current: ≤ 48 kA
Ripple: $\leq 1\%$

Vacuum System:

Four Stage Pump System:

- 1) 3 MTP 50,000 m³/h roots pumps
1 Alcatel 120,000 m³/h roots pump
- 2) 1 MTP 50,000 m³/h roots pump
- 3) 1 multiple slide valve type pump RV 500
- 4) Rotary vane pump BA 600

Total suction power: $> 200,000$ m³/h at 10 Pa
Tank pressure can be set

Vacuum tanks:

8 tanks connected to vacuum system

- 6 for plasma accelerator development
- 2 plasma wind tunnels

2 independent test stands for smaller thrusters or basic experiments



History of MPD Activities at IRS

1976	Begin of Building-Up of IRS Propulsion Laboratory
1982-1991	Cooperation Grants "Basic Processes of Plasma Propulsion" from AFOSR (analytical and numerical).
1982-1991	Cooperation Grants with interruptions "MPD Thruster Development" from AFRPL, AFOSR. 1987-1988 financed by the SDIO over ONR (experimental and numerical).
1989-1991	"MPD Thruster Instabilities", contract by the German Research Organisation DFG (theoretical studies).
1990-1993	"Plasma Instabilities in MPD Thrusters", contract by the German Ministry of Research BMFT (numerical and experimental; together with MAN).



History of Thermal Arcjet Activities at IRS

1986-1990 **"Arcjet Flow Analysis", contract by ESA/ESTEC (analytical and numerical).**

1987-1990 **"1 N Arcjet", sub-contract by ESA/ESTEC (experimental), main-contractor BPD, Italy.**

1989-1991 **"High Power Arcjet", Cooperation Grant by NASA (IST) (experimental and numerical studies).**

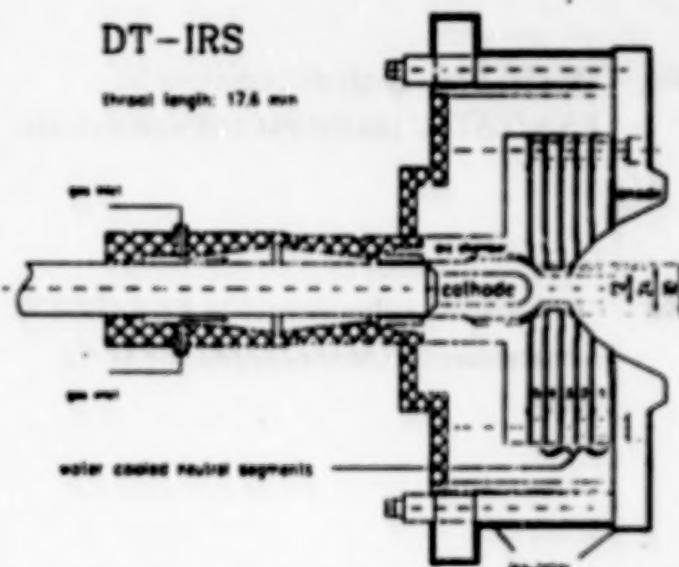
1990-1993 **"A 1 kW Hydrazine Arcjet", contract by the German Aerospace Agency DARA (together with MBB).**



Nozzle Type Thruster DT-IRS

DT-IRS

Overall length: 17.6 mm



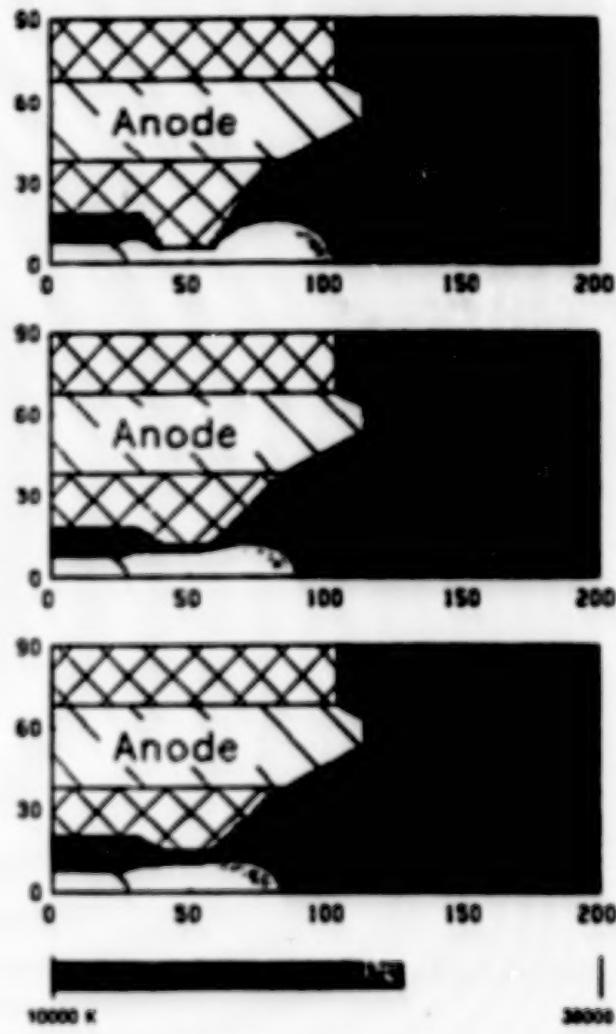
Configuration of the DT-Thrusters with different throat diameters

Maximum values reached with the DT2-Thruster with argon as propellant:

electrical power: $P_e \leq 800 \text{ kW}$

specific impulse: $I_{sp} \leq 1500 \text{ s}$

thrust efficiency: $\eta \leq 25\%$

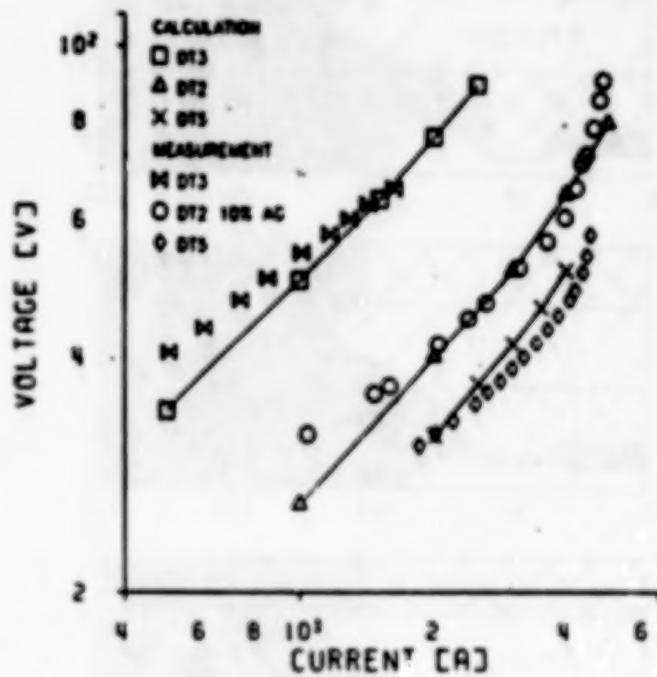


Electron temperature distribution for three different throat geometries at 2 kA current and a mass flow of 0.8 g/s.



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Calculated and measured discharge voltage.



Nozzle Type MPD Thrusters

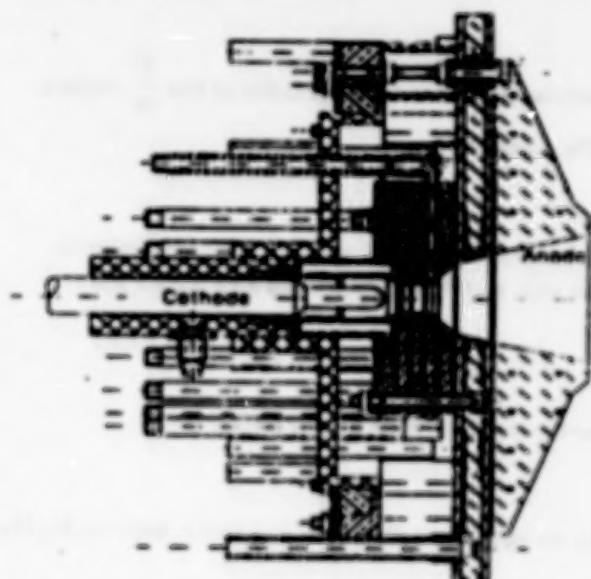
- 1.) Specific impulse limited to 1000 s because of low $\frac{P^2}{m}$ - values.
(Onset - Phenomenon)
- 2.) Efficiency : not more than 30% achieved with experiments.
Expectation with higher massflow rates and higher power:
above 30% .
- 3.) High power limitations: Heat load of nozzle throat.
- 4.) Propellant: no significant difference in η and c_s with Ar, N₂, H₂,
lower $\frac{P^2}{m}$ with H₂ and N₂.
- 5.) High power limits:
vacuum system (high power = high mass flow rates)
(Influence of ambient pressure not so important with
selffield MPD's)

Research plans: Geometry optimization:

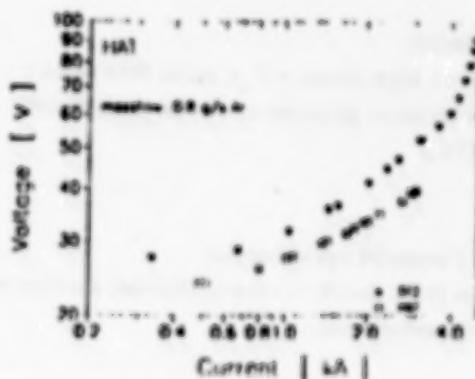
- Transition from nozzle to conical (flared) configurations.
- Radiation cooled anode.



Hot Anode Thruster (HAT)



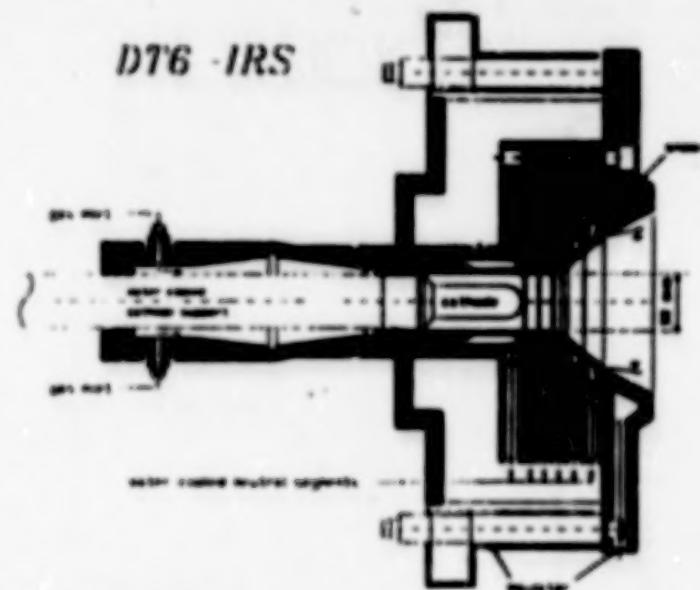
Configuration of the HAT-Thruster with radiation cooled anode



Voltage vs. current dependence for the HAT
in comparison with the BT2-Thruster



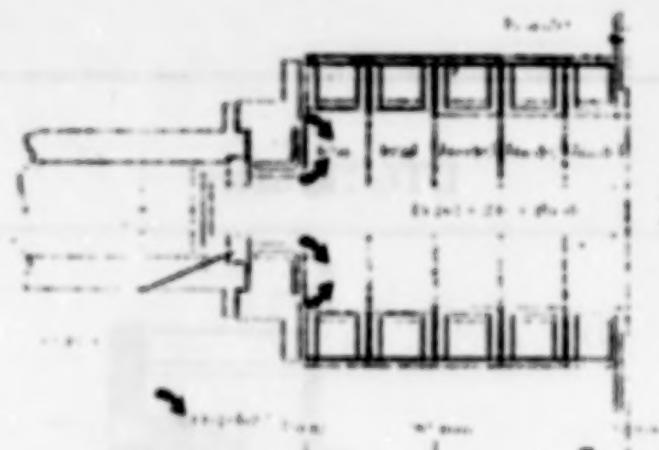
DT6-Thruster



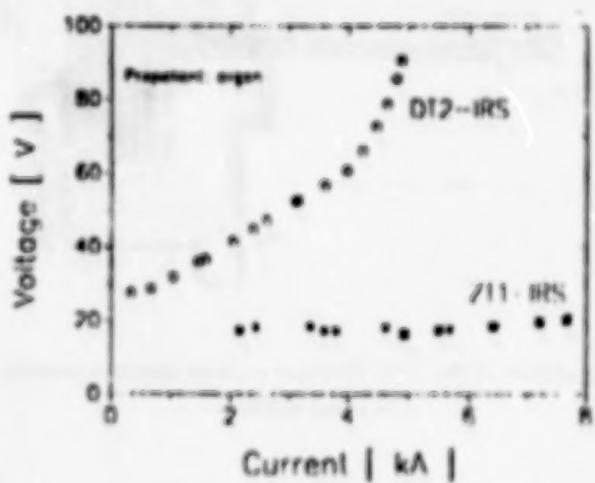
Configuration of the DT6-Thruster without throat constriction
(in construction)



ZT1-Thruster



Configuration of the cylindrical ZT1-Thruster

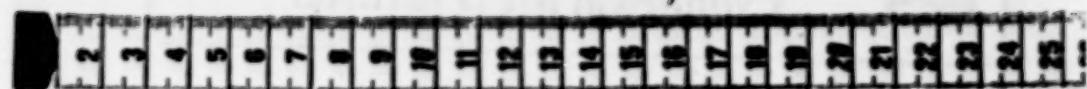


Voltage vs. current dependence for the ZT1- respectively DT2-Thruster with argon as propellant

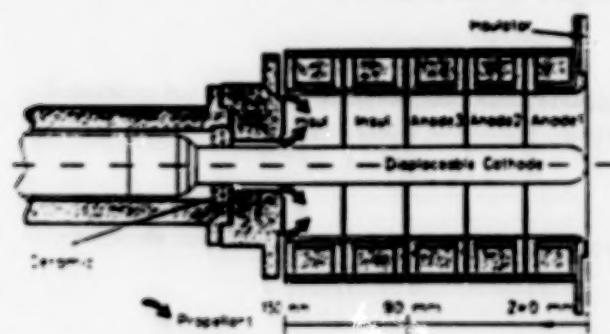


Cylindrical MPD thruster

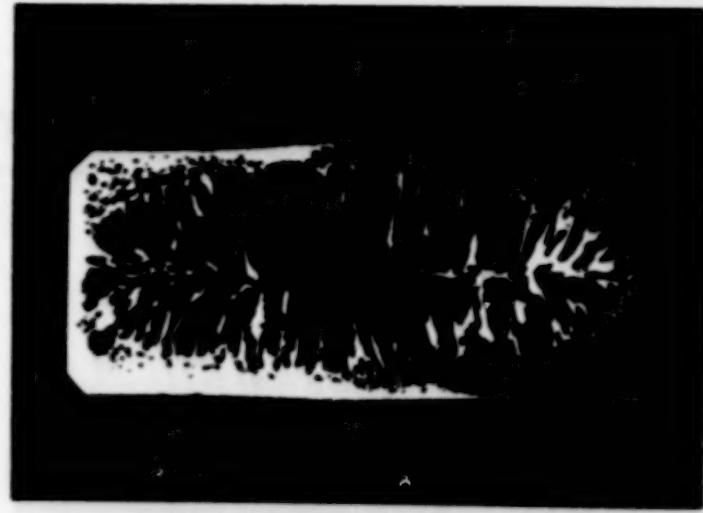
- 1.) Higher onset ($\frac{P^2}{m}$) than with nozzle type thrusters.
→ higher specific impulse possible.
- 2.) Efficiency with continuous thruster not yet measured.
(Thrust balance in construction.)
- 3.) Lower voltage levels than with nozzle type thrusters.
- 4.) High current issues:
 - a) heat loads to anode (~ 1)
 - b) heat loads to cathode: can be solved by cathode geometrical configuration.
- 5.) High power limits:
vacuum system (high power → high massflow rates)
(Not so important with selffield MPD)



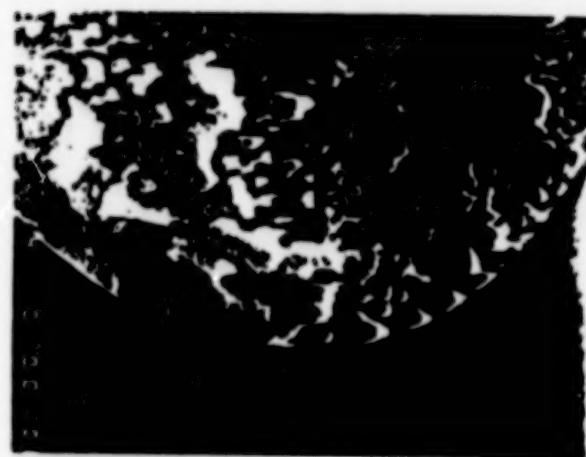
DAMAGED CATHODE OF THRUSTER ZT1



SCHEMATIC OF THRUSTER ZT1



TYPICAL STRUCTURE OF AREA I (MELTED ZONE)



DETAIL OF THE VOID

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Comparison



continuous MPD ↔ quasi-steady MPD

Biggest problem: different cathode modes:

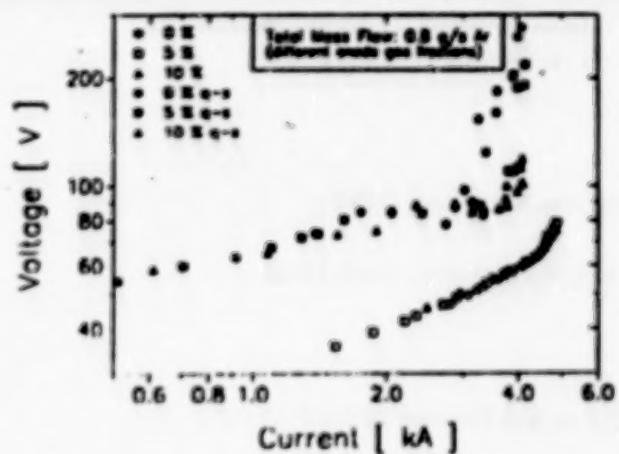
thermionic ↔ cold

- ⇒ different arc attachments
- ⇒ different voltages
- ⇒ different current distributions

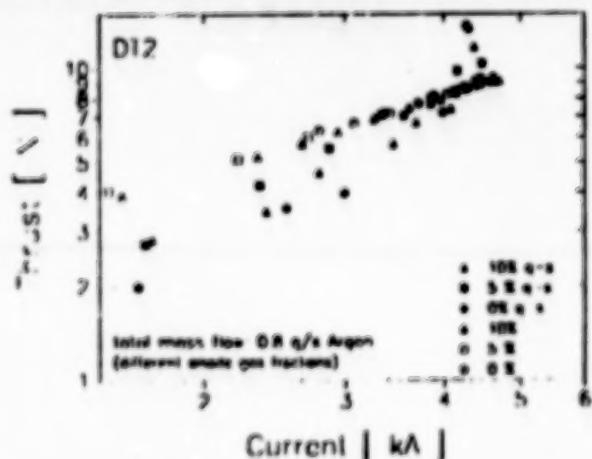
Comparison



continuous MPD ~ quasi-steady MPD



Comparison of the voltage vs. current dependence for the continuous ITT2-Thruster (open signs) and the quasi-steady MPD-Thruster (Closed signs)



Thrust vs. current curves for both thrusters



MPD-Thrusters

1.) Nozzle Type MPD-Thrusters (DT-IRS serie)

- Geometrical optimisation of the nozzle
(experimental and numerical)
- Investigation of the plasma instabilities
(experimental and numerical)

2.) Hot Anode Thruster (HAT)

- Reduction of the anode losses

3.) Cylindrical Thruster (ZT-IRS)

- Thrust measurements will hopefully resulting in

higher c_e !



MMW-Thrusters

MMW thruster have to be cooled actively (at least partly).

Cathodic heat loads could be solved by geometrical configuration.

How to address these issues:

- 1.) Measure heat loads in cooled devices and surface temperatures.
- 2.) Establish thermal models (numerical).
- 3.) Numerical variation of geometries and configurations.
- 4.) Validate with new device.



Facility requirements

1.) Vacuum:

- for selffield MPD better 1 mbar
- for applied field MPD better 10^{-3} mbar

2.) Thrust balances for MMW-Thrusters are difficult to realize.

REPORT DOCUMENTATION PAGE

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